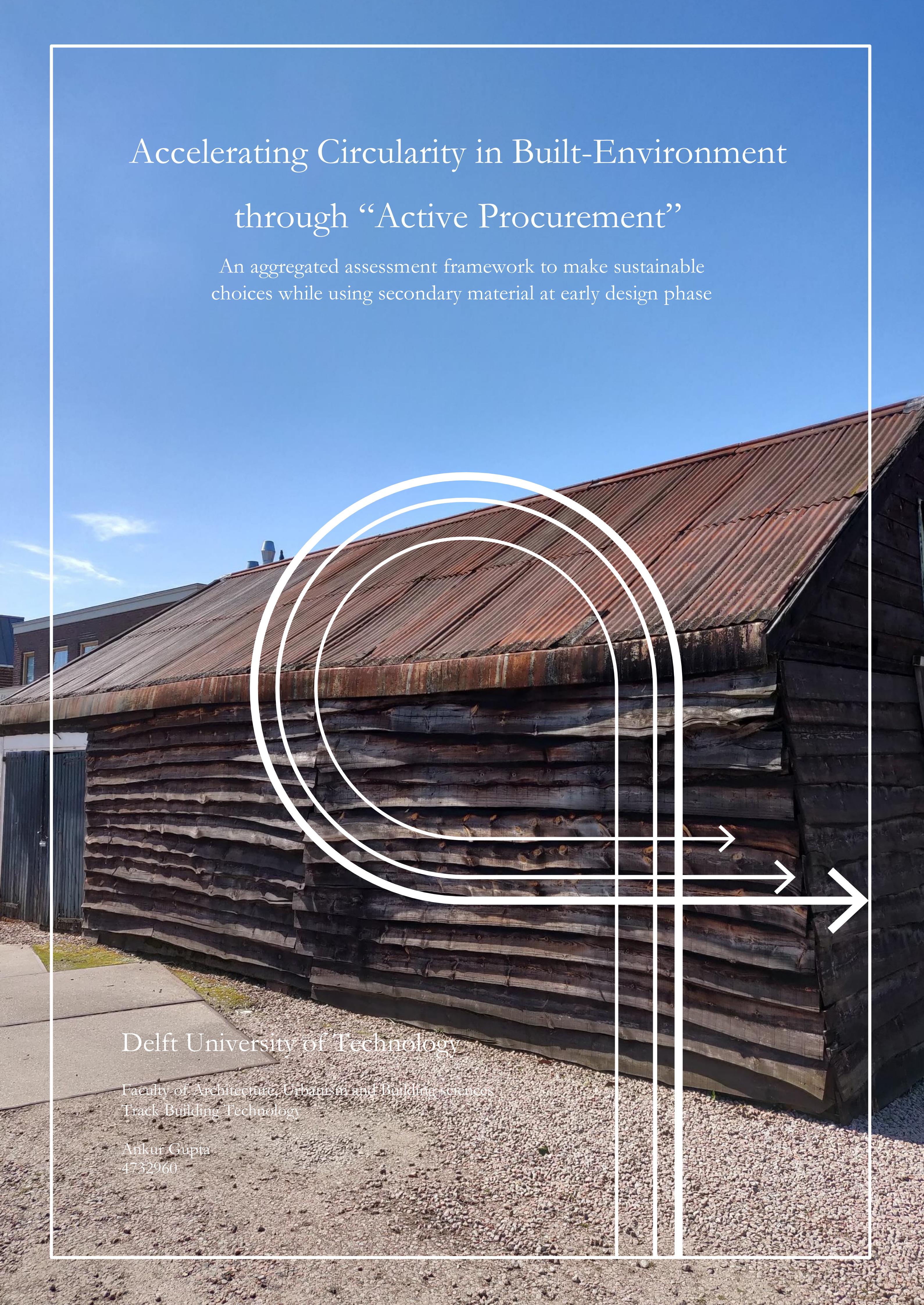

Accelerating Circularity in Built-Environment through “Active Procurement”

An aggregated assessment framework to make sustainable choices while using secondary material at early design phase

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Colophon

Graduation thesis report
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Abstract

In Europe, 1/3rd of all the products reaching recycling facilities can be sold as secondary materials, and this can be a high-quality replacement for low-quality new products. Circular Material Use rate shows how much material demand was catered by reused or recycled content. The Netherlands was estimated at 29% in 2016 is the highest among all other member states and more than twice of Europe's average. The Netherlands has now set up the goal to become 100% circular by 2050. Principles of circularity aim at lowering the environmental impacts and halve the emissions by 2030 and carbon neutral by 2050, according to the Paris Agreement. However, even though high circularity rates in the Netherlands, 12.2 tonnes per capita of greenhouse gases were released in 2016, which is 3.5 tonnes higher than the EU average.

In transitioning to a circular built environment, the most crucial challenge is to keep all materials in a closed loop in a way that proves lower environmental impact compared to extracting a virgin equivalent. In current practice, building materials are procured at the end of a design phase, which results in minimum use of secondary stock and maximum extraction of virgin material to fit "circular" designs. Since buildings are designed for longer lifespans, this virgin material returns as secondary much later and do not indicate the indicator defined by the EU. Hence, we need to focus on reuse, repair, remanufacture, repurpose or recycle.

The main question is what information is needed by a designer or engineer in procuring secondary materials and when & how it can be best provided to them. A 3-tier literature study is conducted to understand assessment of circularity in the Built-environment, case studies with expert interviews and state-of-the-art practices that aim at making this transition. The overall challenge is to provide transparent information about available secondary material and a KPI to ensure sustainable choice at the early design phase.

This research gives an Assessment Framework to assess parameters such as the circular flow of materials, embodied CO2, cost and technical performance while designing. It is composed of five significant interfaces - material database, material explorer, assessment dashboard, digital design and a visual script to assess various parameters such as MCI, embodied CO2, distance from the project site, cost, U-value, Thermal conductivity, Density and other labels in 3D.

The framework provides a Preliminary and Advanced assessment of different parameters. The only difference is that Advanced assessment takes into account is the disassembly potential of various components at a system level and determines whether they can be reused or have to be demolished at EOL. Demolition would mean a product reach EOL sooner, which result in higher embodied CO2. Hence, allowing design/engineering optimization. Other instance, where a component reaches EOL before its surrounding product, replacement of that component should not result in the demolition of others. These components can be identified using the colour-coded interface. These tools can be incorporated within a project or a company to help the transition to a circular built environment.

KEY WORDS
Circular economy, LCA, Design for disassembly, Environmental impacts, Adaptive reuse, Sustainability, circularity assessment, procurement, built environment

Acknowledgments

After pursuing a Bachelor of Architecture and gaining some experience while working as an architect, I wanted to develop more technical knowledge about construction and engineering. I was always interested in engineering sustainable solution using parametric tools. My decision to pursue building technology course at TU Delft has surely elevated my technical knowledge and also exposed me to an industry that continually pushes its limit.

This thesis started with curiosity and sympathy towards sustainable goals of circularity. It challenges our profession and forces us to think beyond our existing knowledge. It is promoting an amalgamation of architecture, engineering and construction as it was centuries ago but for a sustainable future.

I want to thank my parents and my sister for being strong enough to support me financially and emotionally to pursue my ambitions and education at TU Delft. They are the most hard-working people I know, which inspires me every single day.

It was inspiring to be mentored by Tillmann Klein and Peter Russel throughout these 7 months. I want to thank them for keeping an open mind and let me pursue my graduation thesis on the topic accelerating circularity in the built environment. Their expertise in building products and computation in architecture has proven to be a good collaboration for this thesis.

Tom Blankendaal has been continuously inspiring, motivating and positive about my research outcomes. So I would like to thank him for supporting my ideas and opinions under the umbrella of circularity group at Royal BAM Group n.v. Collaboration with him was both professional and friendly.

Marcel Tabak has proven to be a good point of contact at ABT b.v. for connecting me with various experts in the field of sustainability and BIM. I want to thank him and Jeroen ter Haar for providing me with the opportunity to utilize the necessary resources to conduct my research.

At last, I would like to thank all the experts I interviewed and talked throughout the process.

I commit to help further create a more sustainable world for generations to come.

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Chapter 1. Introduction

This Chapter formulates the context of this thesis. The first section marks the urgency of the need to change current practices to fit the goals of a circular economy. The second section describes the research objectives and limitations of the study.

1.1 Context of the research

1.1.1 Construction and Demolition waste in Europe

In Europe Construction and demolition activities accounts for 25%-30% of all non-hazardous waste It is also the heaviest and more in volume compared to other waste streams. It majorly consists of glass, brick, wood, metals, plastics, gypsum, concrete and excavated soil. Construction and Demolition waste (CDW) is generated while constructing a new building, roads, maintaining infrastructure, and renovation activities. EU construction & demolition waste management protocol includes a pre-demolition audit to find a potential for the material that is recyclable, reusable, energy recoverable. Direct re-use of material poses as the most environmentally friendly than recycling, recovering or backfilling. Backfilling is the most dangerous practice and contradicts the circular material use rate. For effective waste management, landfill restrictions must be made for recyclable materials. Also, higher taxes could become a powerful tool to derive a market for recycled and secondary materials (European Commission, 2016).

The most environmentally and economically viable material to re-use are metals, plastics and glass. However, these materials would not reflect in the overall recovery rates because of the dominance of material like concrete or earth in total mass that is recovered in demolition (European Commission & Joint Research Centre, 2016).

Apart from the primary function of a building, the design should also ensure material is used for various lifecycles. Use of standardized components or use of available feedstock to create new products should be prioritized rather than designing on a blank canvas (De los Rios & Charnley, 2017).

1.1.2 CDW management in Netherlands

Netherlands has been recycling CDW since the 1980s as an aftermath of contaminated soil issues due to the landfilling activities. A waste hierarchy was developed as a response where new policies banned landfilling and new recycling targets were set. A nation-wide plan for managing CDW was developed involving all stakeholders. The main task for the recycling industry is to ensure quality. The inert CDW was crushed into aggregate and used as backfilling, after being sorted into wood, plastics and inerts. As the recycling process improved, recycled aggregate is also being used in the production of new concrete. Asphalt and wood are recycled at high rates where 100% asphalt is recycled into new; wood still forms part of biomass for energy generation. Other materials such as flat glass, PVC windows can be delivered to collection points for free via schemes. Gypsum is kept separate from the inert CDW so that the quality of recycled aggregate is not affected (European Commission, 2016).

1.1.3 EU goals for circularity

"In December 2015, the Commission adopted a Circular Economy Action Plan 1 to give a new boost to jobs, growth and investment, and to develop a carbon neutral, resource-efficient and competitive economy. The 54 actions under the action plan have now been completed or are being implemented, even if work on some will continue beyond 2019"(European Commission, 2015).

The European Union have launched two circular economy packages to encourage and steer the transition for becoming a more circular economy (European Commission & Joint Research Centre, 2016). The monitoring framework presented by the EU provided 10 key indicators to track the transition towards a circular economy (European Commission, 2019c). All these indicators are available on a dedicated website and updated regularly (European Commission, 2019a).

According to European Union's Seventh Environment Action Program, Europe needs to become a "resource efficient, low-carbon economy" (European Environment Agency, 2017). Guidelines for waste audits before demolition and renovation will lead to the identification of materials that can be re-used or recycled. This will also keep in mind the market for CDW locally (European Commission, 2018b).

(Leising, 2015)'s one of the major findings concerning the circular supply chain was the need to build a market place where used products and resources can be exchanged. In future apart from energy efficiency-reparability, durability, upgradability will be systematically examined (European Commission, 2015)

About 1/3rd of the products that are sent for recycling in Europe are directly re-usable and can be sold as secondary materials. If this material is supplied back in the economy, not only material efficiency increases but also create jobs in the second-hand market sector in the EU. Use of secondary material is an essential contributor to the circular economy if the development of re-use centres and networks, including enabling technologies, is supported. The use of a second-hand product can be a high-quality replacement for low-quality new product (European Commission, 2019b).

1.1.4 Netherlands goals

The Government-wide programme for Circular Economy, 2016 presents the goal of circular economy in the Netherlands by 2050. Together with a variety of stakeholders, and interim objective is to reduce the consumption of primary raw material by 50% till 2030. According to the Netherlands Organization for Applied Scientific Research (TNO), a turnover of €7.3 billion accounting up to 54,000 jobs can be added annually. Also, the use of raw materials can be reduced by 100 megatons, which are equal to 25% of the annual import of raw materials.

Three objectives are set up to accelerate the transition of the current Dutch economy into a circular economy. Firstly, the raw materials in the existing supply chain must be used in a high-quality manner. Secondly, where the new raw material is needed, non-sustainably produced materials should be replaced by sustainably produced ones to reduce the dependence on fossil fuels. Thirdly, new production and consumption methods that give desired reduction, replacement and utilization.

In the construction Industry, almost all CDW is processed to be used as a filler material (backfilling) in groundwork and construction of roads, rather than being reused to its highest quality. More considerable attention will be given to product's environmental performance and social costs at EOL, and this will be done by engaging circular procurement accounting for 10% share by 2020 (Ministry of Infrastructure and the Environment, 2016).

1.2 Research Objectives

1.2.1 Problem statement

In response to becoming a circular economy, first and the most obvious challenge is to reuse materials. In built-environment, whether it is flooring, wall cladding, windows or doors, all materials must be reused to its full potential and highest value before dispatching it to a process of remanufacturing, refurbishment, recycling or disposal. The classical and current approach of procurement of building material comes at the end of a design phase. This enables freedom in design but leads to the procurement of more new material than secondary. This is because of the nature of the fixed design. In the case of a circular economy, extraction of virgin material needs to be minimized by the use of second-hand material.

To reuse secondary material, it is essential for designers and engineers to know what is available. Hence, the knowledge of availability should become the first step in any design process. Online marketplaces are hosted by suppliers to facilitate this information. These marketplaces usually lack effective communication with the designers due to insufficient qualitative and quantitative documentation of the available stock. This prevents the use of secondary material at a wider scale and accelerated rate.

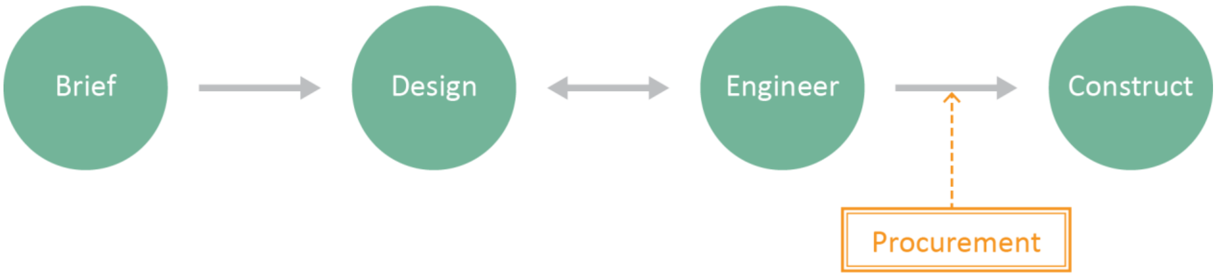


Figure 1.2.1 Simplified depiction of current design and construction practice where procurement of materials comes after fixing the design and details of the building, thus preventing maximum use of secondary materials, Source: own illustration.

1.2.2 Main objective

The main aim of this thesis is to be to propose an effective way to accelerate the use of secondary materials by designers and engineers up to the highest value. Doing so maintaining its circular flow at the end of use and low environmental impacts.

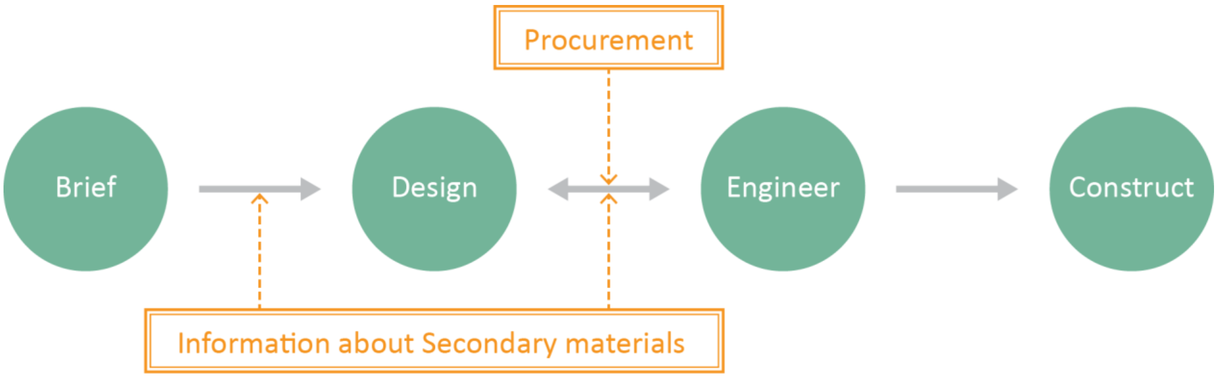


Figure 1.2.2 Simplified depiction of bringing the information about secondary material at early design and engineering phase.

It is crucial to understand circularity concerning buildings To achieve this objective. Since buildings are composed of various components with nested elements, it is complicated to derive circularity of a building before engineering. State-of-the-art practice circularity indicators are being developed to measure a building's circularity. It is essential to understand the potential and fallbacks of the method used currently. Hence, a strategic literature study is carried out in further chapters to understand key components of measuring circularity, case studies and state-of-the-art material databases.

1.2.3 Main research question and sub-questions

What information is required by a designer to use second-hand material in building design – ensuring circular flow of materials at end of use, low environmental impacts, cost and energy consumption? And when and how should it be provided to them?		
Chapter 2	1.	How does circularity affect environmental impacts?
	2.	What are the important key indicators for monitoring circularity in built environment?
	3.	How does a building component affect the circularity of the overall building?
	4.	How to measure circularity of a building at early design phase?
Chapter 3	5.	What key parameters are needed in making a decision to utilize secondary material at early design stage?
	6.	What are the challenges of circular procurement and construction?
Chapter 4	7.	What parameters should be implemented in material databases to accelerate use of secondary materials?
	8.	How the use of secondary material be accelerated? How to integrate material database in the design process?

Table 1.2.1 Main question and sub-question, and the chapters they are answered in.

1.2.4 Research approach

A 3-tier literature study is conducted to achieve the main objective. The expectations were to find a solution within this domain of knowledge. These three studies form three different chapters in the report. **Figure 1.2.1** shows the main structure of the report.

Chapter 2 covers the concept of a circular economy and complimenting concepts with similar aims. It can be learnt from this chapter how EU track progress towards circularity and how to determine the circularity at a product or system level. The factors affecting the calculation of the circularity is its reuse potential, which in case of the building is determined by the physical connections between different components. The conceptual challenges that are faced while determining these aspects for a component within a building are also covered in this chapter. This chapter provides key performance indicators for evaluating circularity and environmental impacts of a circularly flowing material.

Circularity is assumed to lower negative environmental impacts, while in practice, other challenges prevent the use of some secondary materials. This is because it is economical to procure new material rather than processing the existing stock. This can be due to several reasons ranging from location, costs associated with repair and refurbishment or quality assurance.

Chapter 3 covers the challenges of using secondary materials via case studies and interviews. These challenges become part of the information that can be documented while mining building materials. This chapter aggregates the key information needed by architects that could help extensive procurement of secondary material while designing. This will be referred to as called 'Active Procurement' in this report.

Some requirement that emerged from Chapter 3 were used as background queries for the literature in Chapter 4. It was essential to know the design requirements to identify the fullbacks in the state-of-the-art database management techniques and what keys components can be carried forward in the final proposal. This chapter shows the study of digital database management tools, existing stakeholders and projects that use such technologies. This chapter concludes the necessary features required in addition to a material database to use it in the design process actively.

The aggregated information from Chapter 2, Chapter 3 & Chapter 4 answers the various question but also raises new questions related to the technological bridges to establish the connection between material database and designer. However, in Chapter 5, an Assessment framework is proposed to bridge this gap, and Chapter 6 demonstrates how this framework helped to make sustainable choices in a small design study.

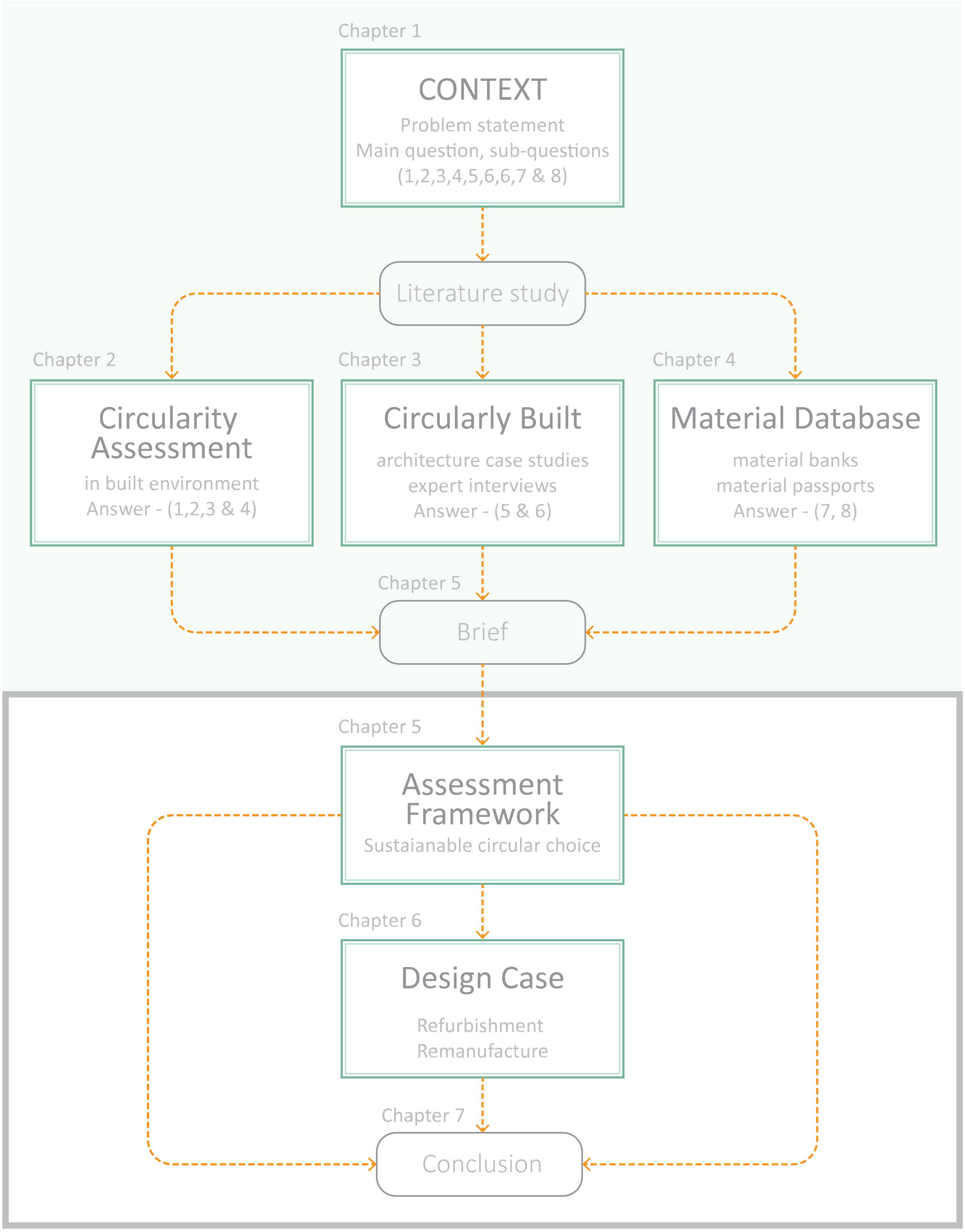


Figure 1.2.3 Report structure, own illustration

1.2.5 Limitations of the research

Circular economy brings various challenges ranging from the business model, material utilization and adaptable design. Life cycle assessment is a massive challenge because new business models shall propose a longer life span to keep the material in circular flow for a longer duration. Also, nested components of a product have different life expectancy compared to just concrete or wood structural components. This research does not focus on administering proper LCA of secondary/circular products. However, to visualize the impact of embodied CO2 of nested components throughout the defined lifecycle of a product, life cycles are defined by using Material Circularity Indicator (MCI) (introduced in Chapter 2).

It is also essential to distinguish between the embodied CO2 versus generated CO2 throughout different lifecycles. As embodied CO2 is the CO2 generated in the past, it should not be fed again in the EU level calculation of CO2 generated per year. It is essential to compare the CO2 generated per year in a life span versus a linear product of limited technical lifespan to track the progress in reducing CO2 footprint and benefit of using secondary material. The research does not support defining the LCA of circular products. External third-party tools need to be used to perform whole lifecycle assessment, which complies with the following standards-

- ISO 1044 2006 (LEED supported)
- NEN EN 15978 (BREEAM supported)

MCI discussed in Chapter 2 considers the quantitative estimate of the fraction of virgin, re-used, recycled, reusable, recyclable content and unrecoverable waste that is generated in a life cycle of a material. It is assumed that a lower amount of virgin raw material, recycling and unrecoverable waste will reduce the negative environmental impacts of building materials.

The focus of the research is to make better-informed decisions to procure secondary material in the early design phase. These materials are assumed to be extracted from a building at its end-of-use and transported directly to the new project site. This embedded CO2 is considered in the indicators in Chapter 2, including the CO2 embedded in recycling and landfill. However, the CO2 embedded in refurbishing the materials in between a lifecycle is not considered as the data is unknown.

Transformation capacity of secondary material is considered 0 because the assumption is that they are not designed to disassemble. Hence, the life-span of the product is the minimum value of the life-span of individual components. For products that are designed for transformation, Transformation capacity described in (Durmisevic, 2006) can be considered in order to determine the life expectancy of the product.

1.2.6 Relevance to circularity goals

To ensure a circular flow of building materials and to make the Netherlands a self-sustaining economy, everyone needs to work together. Current trends of architecture, engineering and construction are divided professions and roles. Construction and demolition companies are usually the owners of the discarded materials which end up in landfill or recycle if the potential of re-use is unknown. Providing access to these discarded materials at the early design/engineering stage would provide the opportunity to add value to the products and give a second life, which was not thought of before. Also, this will educate how to design while keeping in mind the sustainability gains of re-using a second-hand material.

1.2.7 Terms and definitions

Term	Definition
Life cycle	"consecutive and interlinked stages of a product system, from raw material acquisition or generation from natural resources to final disposal" ISO 14044-2006
Life Cycle Assessment (LCA)	"compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle" ISO 14044-2006
LCC	Life Cycle Coordination
Active Procurement	This refers to the act of exploring the use of secondary materials digitally at early design phase. It does not refer to purchasing of the materials.
MCI	Material Circularity Indicator
PCI	Product Circularity Indicator
SCI	System Circularity Indicator
BCI	Building Circularity Indicator
GWP	Global Warming Potential
LFI	Linear Flow Index
CDW	Construction and Demolition Waste
TC	Transformation Capacity
DfD	Design for Disassembly
EOL	End Of Life
EPD	Environmental Product Declaration

Chapter 2. Circularity in the built-environment

This chapter includes a wide range of information regarding the circularity in the Built environment. First three sections introduce the concept of circularity and approaches that focus on the re-utilization of products at end-of-use. Last three sections focus on measuring circularity at three scales- EU, Building and Product level. This chapter concludes how to sustainable and circular choices.

2.1 Circularity Economy concept

(Henry, 2018) Explains the origins of the idea of a circular economy by Hofman (first President of the Royal Society of Chemistry) in 1884 and the term Circular economy by Kenneth Boulding (1966) followed by the term closed-loop economy. All were referring to the idea that the way current economy design, produce, use, distribute and discard has a direct impact on the economy, society and environment. In the current economy, the product is discarded at the end of its service life, and the material it constitutes are either not recycled efficiently and results in loss of this material resource. This is mainly because production costs do not reflect their environmental and societal costs. Whereas in a circular approach, the products should maintain their value for as long as possible. This can be achieved by the way people design, use and maintain. Hence, the design of durable and repairable products becomes necessary (European Commission, 2019b).

To accelerate the transition to a circular economy, the Ellen MacArthur Foundation was created in 2010 to work in three main areas – insight and analysis, business and government, and education and training. Three principles are proposed to define the circular economy. Firstly, by preserving and enhancing natural capital by controlling limited stocks and balancing renewable resource flows. Secondly, optimise resource yields by circulating products, components and materials in use at the highest utility at all times for both technical and biological cycles. Thirdly, foster system effectiveness by eliminating water, air, soil, noise pollution and adverse health effects related to resource use (Ellen MacArthur Foundation, 2015).

2.2 Cradle to Cradle approach

In 1990s Prof. Dr Michael Braungart, William McDonough and the EPEA's scientist in Hamburg developed a design concept called Cradle to Cradle (C2C). It is a concept inspired by nature where products are created according to an ideal circular economy. Its implementation shows not only negative environmental impacts but also creates social, economic and ecological benefits. The concept distinguishes two nutrient cycles- Technical and Biological, as shown in **Figure 2.2.1**. The Biological cycle consists of materials can be decomposed and returned to nature so that new materials can be obtained from it. Whereas, Technical cycle consists of material that can be reprocessed to use in another product (EPEA, 2019).

> *"Waste materials in an old product become the "food" for a new product."*(EPEA, 2019)

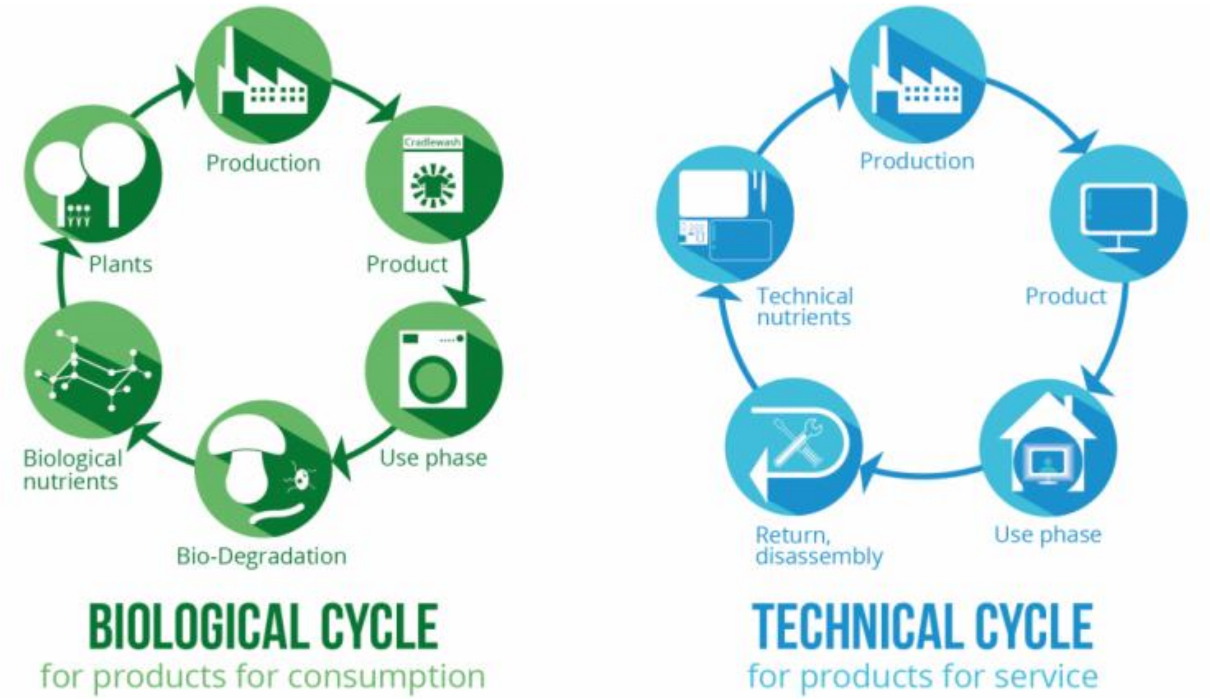


Figure 2.2.1 Cradle to Cradle's two nutrients cycles – Technical and Biological, Source: (EPEA, 2019)

Cradle to Cradle certification program aims at transitioning from the way we manufacture, use and reuse our natural resources to lower the negative environmental impacts. Cradle to cradle design is about choosing the right techniques and applying them correctly to make our processes efficient and environment-friendly. Our natural environment does not recognise the concept of waste as one by-product is a raw material for another and hence cradle to cradle follows the following three principles –

1. Eliminate the concept of waste – Continuous use of material in one product or the other
2. Use renewable energy – Use of solar, wind, hydropower, biomass and other renewable sources
3. Celebrate diversity – benefit social, cultural and ecological footprint

Products seeking to be certified from Cradle to Cradle are assessed on the following categories-

1. Material Health
2. Material Reutilization
3. Renewable energy and Carbon management
4. Water stewardship
5. Social Fairness

The program is based on a binary model with continuous improvement. It has five certification levels- Basic, Bronze, Silver, Gold and Platinum. The standard requirements across five categories can be found in (Cradle to Cradle, 2016).

One of the primary assessment criteria – Material Reutilization relates to the principle of a circular economy to keep the material inflow as long as possible. The program challenges companies to develop products and procedure for recycling and recovery of Technical and Biological nutrients. Material Utilization Score measures it by using **(Eq.1)**.

$$\frac{\begin{bmatrix}\%\,recycled\ or\ rapidly\\ renewable\\ product\ content\end{bmatrix} + 2\begin{bmatrix}\%\,of\ product\ recyclable\\ or\ biodegradable/compostable\end{bmatrix}}{3} \times 100 \qquad \textbf{(Eq.1)}$$

Where recycled material is the percentage of material collected after the consumer use and the waste material that is collected for recycling during the manufacturing process. Rapidly renewable material is a material that is grown and harvested in less than ten years per cycle, recyclable material is a material that can be recycled at least once after first use or materials that can be incinerated to produce energy. Compostable materials are those that can undergo biological decomposition. A level is given based on the score range shown in **Table 2.2.1** (Cradle to Cradle, 2016).

LEVEL	ACHIEVEMENT
BASIC	Each generic material in the product is clearly defined as an intended part of a biological or technical cycle (this is covered by the Material Health requirement at Basic level
BRONZE	The product has a Material Reutilization Score that is ≥ 35.
SILVER	The product has a Material Reutilization Score that is ≥ 50.
GOLD	The product has a Material Reutilization Score that is ≥ 65. The manufacturer has completed a "nutrient management" strategy for the product including scope, timeline, and budget.
PLATINUM	The product has a Material Reutilization Score of 100. The product is actively being recovered and cycled in a technical or biological metabolism.

Table 2.2.1 Material reutilization requirements for various levels of C2C certification, Source: (Cradle to Cradle, 2016)

2.3 Design for Disassembly

Design for Disassembly (DfD) aspects were developed by Durmisevic & Brouwer in 2006 to formulate a knowledge model to help build highly transformable structures to cater the dynamically changing needs of 21st century. Demolition activities due to functional changes lead to loss of material and energy. Building material does not last up to their 'technical life cycle' because of the decreasing 'use life cycle'. This has resulted in increased consumption of resources and adverse effect on environment. By increasing the life cycle of a buildings and materials we can ensure saving energy, reduce waste and natural resources. This can be done by extending the life cycle of the building and allowing for flexibility and adaptability. DfD aspects provided a framework to design highly transformable structures at all levels to adapt to change and ability to upgrade without complete demolition. These DfD aspects aggregate and define Transformation Capacity (TC) of any structure which will be discussed in section 2.5.

Apart from Transformation capacity, a new ISO standard 20887 for Design for Disassembly and Adaptability of Buildings is under development by TC 59/SC17, Although it is not clear whether it will result in a quantifiable design assessment tool (Cornet, den Berg, & Oorschot JAWH, 2016).

DfD is directly related to low negative environmental impacts as material can be extracted for re-use, recycle or refurbish. Transformability can be divided in three major categories-

1. **Functional decomposition**- checks if a building product performs more than one function. If product needs to be transformed, it should not affect other functions.

2. **Technical decomposition**- studies the hierarchy of a product composition and whether there is dependency between different functional groups.

3. **Physical decomposition**- evaluates the design of connections between components

Figure 2.5.1 illustrates the classification of these categories into DfD aspects, which are further classified into sub-aspects in **Table 2.5.1**.. The influence of each sub-aspect is calculated by an assigned weighted factor ranging from 0.1 – 1.0 and between the eight aspects based on influence on transformability (refer **Figure 2.5.1**). Higher Transformation Capacity of the building would result in high adaptability towards change in function; building products can be replaced, reused or recycled.

The Assembly and Disassembly sequence, Connection, Geometry of product edge and Life Cycle Coordination are four of the eight aspects of DfD. The type of connection between components defines how much time it takes to assemble and disassemble a product. Also, if two components are connected with a chemical bond, then their transformation is not possible, and demolition would be the only way to take them apart. Similarly, a dry & flexible joinery would enable transformation of either of the components without damaging the other. If these conditions are applied to buildings systems at all levels, all the systems are then demountable, components are replaceable, and all materials are recyclable. **Figure 2.3.2** describes 7 principle connections ranging from fixed to flexible.

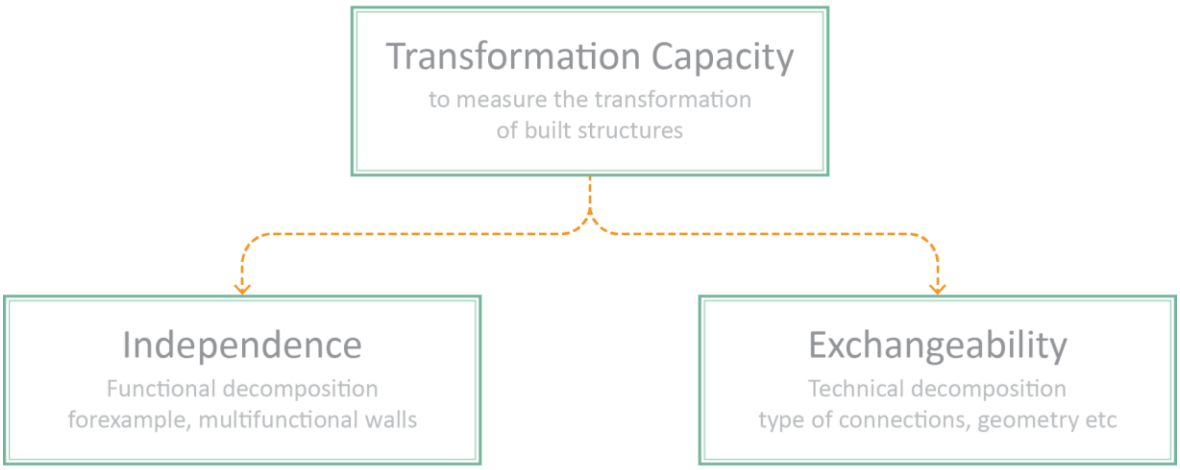


Figure 2.3.1 Dependence of Transformation capacity on Function and Technical separation, own illustration

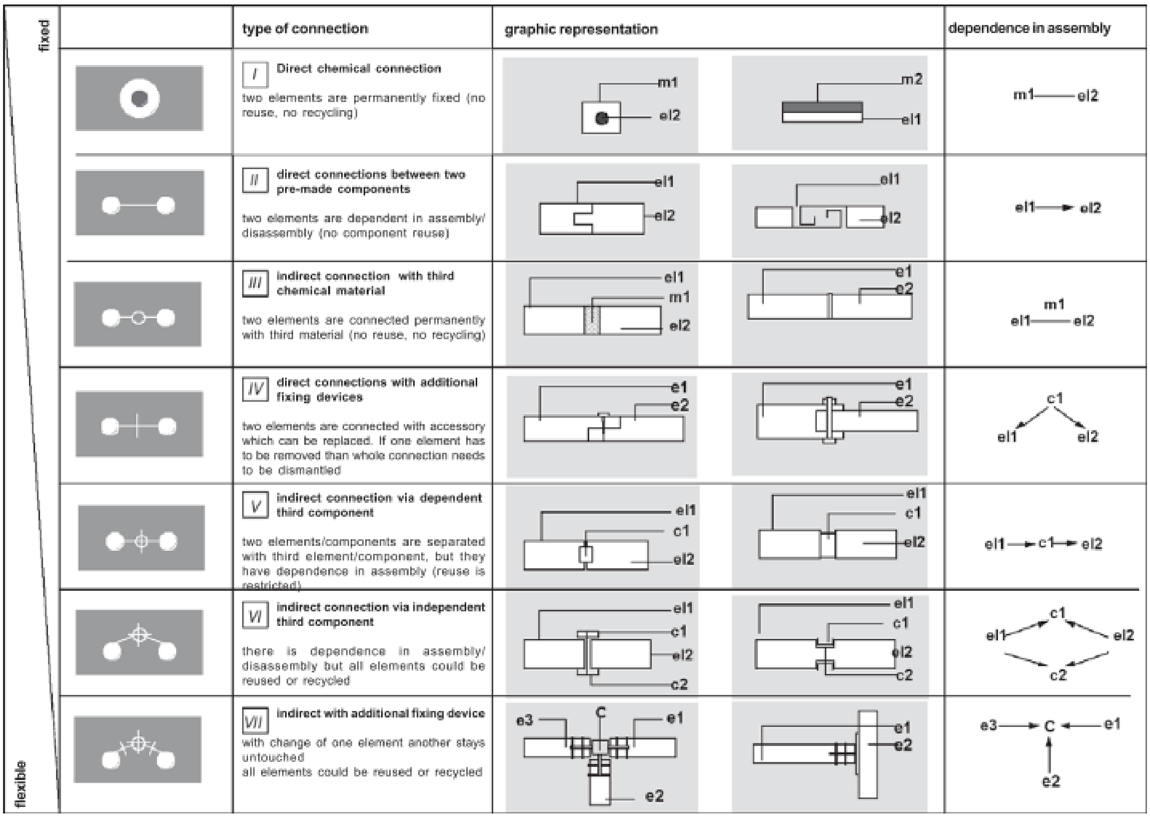


Figure 2.3.2 Connection principles ranging from permanent to flexible (Durmisevic & Brouwer, 2006)

After the type of connection, Geometry of product edge influences the process of disassembly. Either the edge can be open or interpenetrating with another component. Interpenetrating geometry is less suitable for disassembly and cause damage while trying to take the component apart. **Figure 2.3.3** shows 6 standard type of product edge that are often used in housing projects in Netherlands.

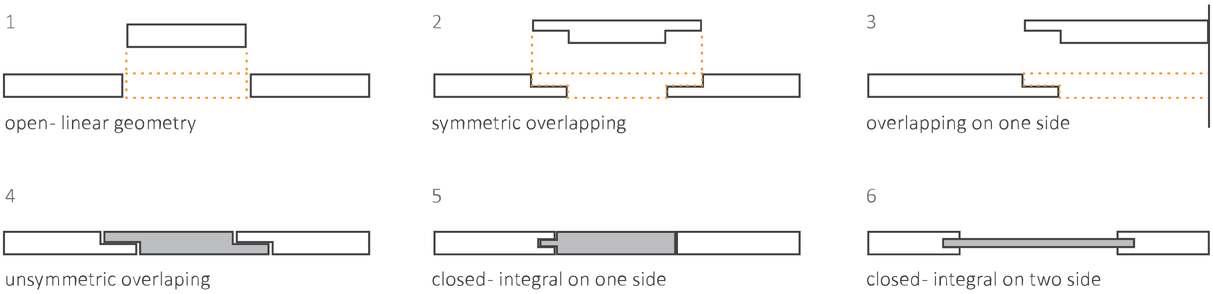


Figure 2.3.3 Six Geometry of product edge influencing the level of physical decomposition and transformation level of configuration (Durmisevic & Brouwer, 2006), own reinterpretation

After ensuring that product edge favors the disassembly, aspect of Life Cycle Coordination becomes important. This can be analyzed by studying the Assembly and Disassembly sequence of a system. Components with higher life span should be installed first because they are less likely to be transformed frequently. Whereas components with shorter life span should be assembled last so that they can be disassembled first. Due to later assembly, there is less dependency on other components as well. This can be illustrated by assembly & disassembly diagram as illustrated in **Figure 2.3.4**. In a) element 2.22 has a shorter lifespan and is seen to be assembled first. Disassembling this element for repair would mean disturbing all the elements. Hence, reducing the lifespan of the whole structure. In b), a new detail is proposed where an element with the similar function has a longer lifespan and can be disassembled almost at last. It gives an opportunity for replacement of other elements with maybe shorter lifespan without demolition of the others.

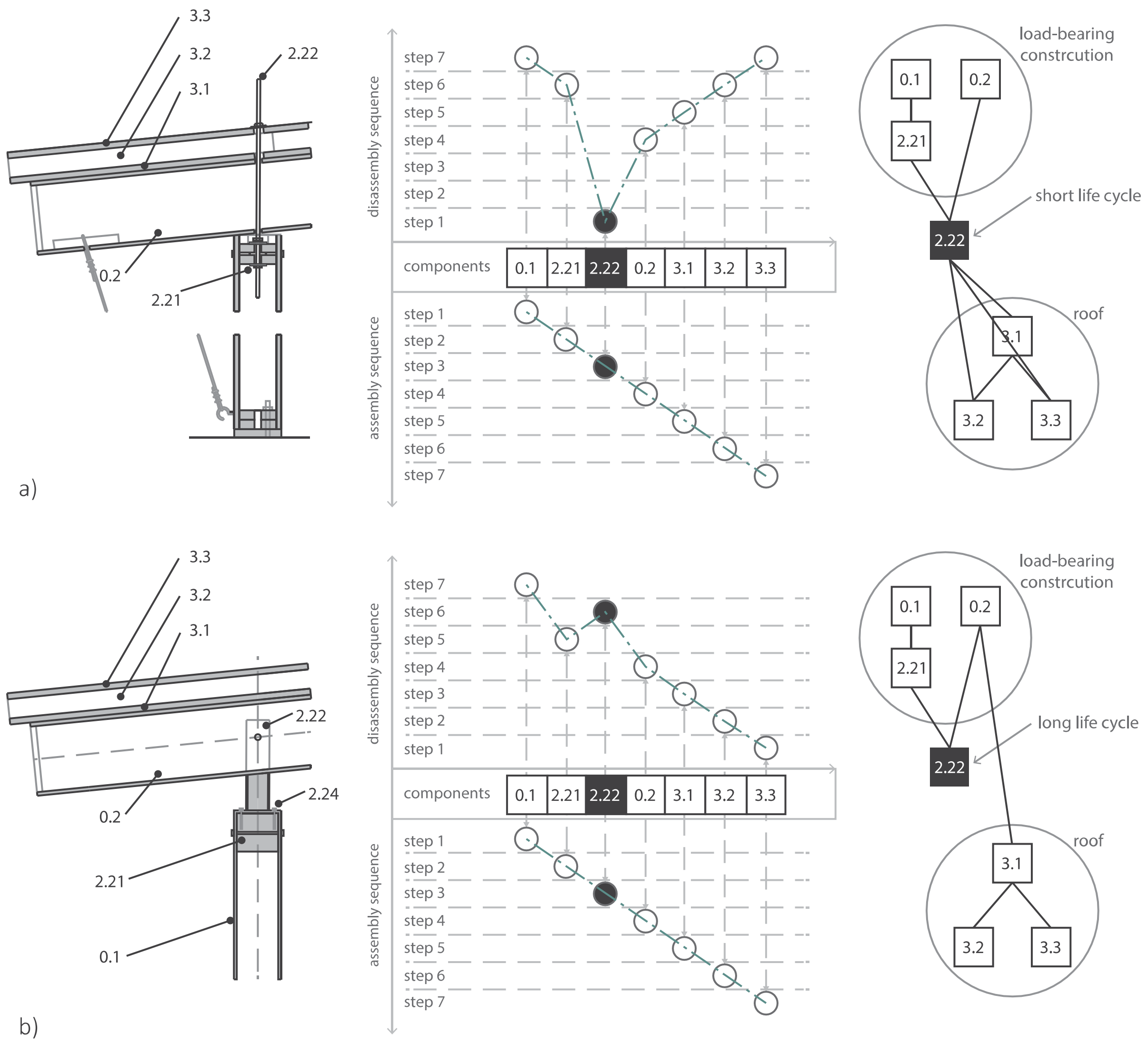


Figure 2.3.4 Assembly and disassembly sequence compared with life span of a component (Durmisevic, 2006), own reinterpretation

2.4 EU Circularity indicators

CDW is the biggest source of waste in Europe. In 2014 it accounted to 33.5% of the total waste in EU-28. It has been realised that these materials need to be circulated back into the economy and also using it to its highest potential. European commission has developed a framework to monitor circular economy. The framework aims to measure the progress and effectiveness of the action within Member States and overall EU status. With this, success can be assessed of various policies as well as more efforts can be made wherever required. There are 10 main indicators sub-divided into 26 sub-indicators. The framework consists of four major categories- Production and Consumption, Waste management, Secondary raw materials, and, Competitiveness and innovation. Most critical w.r.t raw material and recycling is explained below (European Commission, 2018c).

2.4.1 Recovery rate of CDW

In CDW industry most of the materials can easily be recycled, hence, proving that it can be a good source for secondary raw material. Within EU almost 88% of this waste was recovered in 2014. An increase of almost 10% has been noted since 2010. The recovery rate of CDW is higher than 90% in 17 of the member states. With huge variation between member states, 11 of them have more than 95% recovery rate, whereas 2 falls under 40%. In Netherlands however, it is 100%.

The recovery rate can be defined as the ratio of CDW that is re-used, recycled, recovered or used in backfilling, to the total sum of CDW collected. This fills the category 'Mineral waste from construction and demolition' where only non-hazardous waste is considered (European Commission, 2018c) (European Commission & Joint Research Centre, 2016).

Metals, glass, plastics etc. require high amount of energy to be produced and are the most valuable CDW. They account for only small percentage in this indicator. Even though high reuse and recovery rates for these elements would deem fruitful sustainability gains, it would not be reflected in this indicator effectively.

2.4.2 Circular Material Use rate

Circular Material Use rate (CMU) is essential to measure the circularity of economy. The aim of this indicator is to increase the amount of recycled stock and supply back in the economy. This would reduce the extraction of primary raw material.

It is defined as the ratio of recycled waste material over the total material demand. It can be calculated as the ratio of secondary raw material to the overall material consumption. **Figure 2.4.2** shows the progress over years for circular material use by material category. The overall trend is still positive. In **Figure 2.4.3**, countries that have high CMU rates have either high rate of waste recycling or low level of Domestic Material Consumption (DMC) or both. Netherlands has a rate of 29%

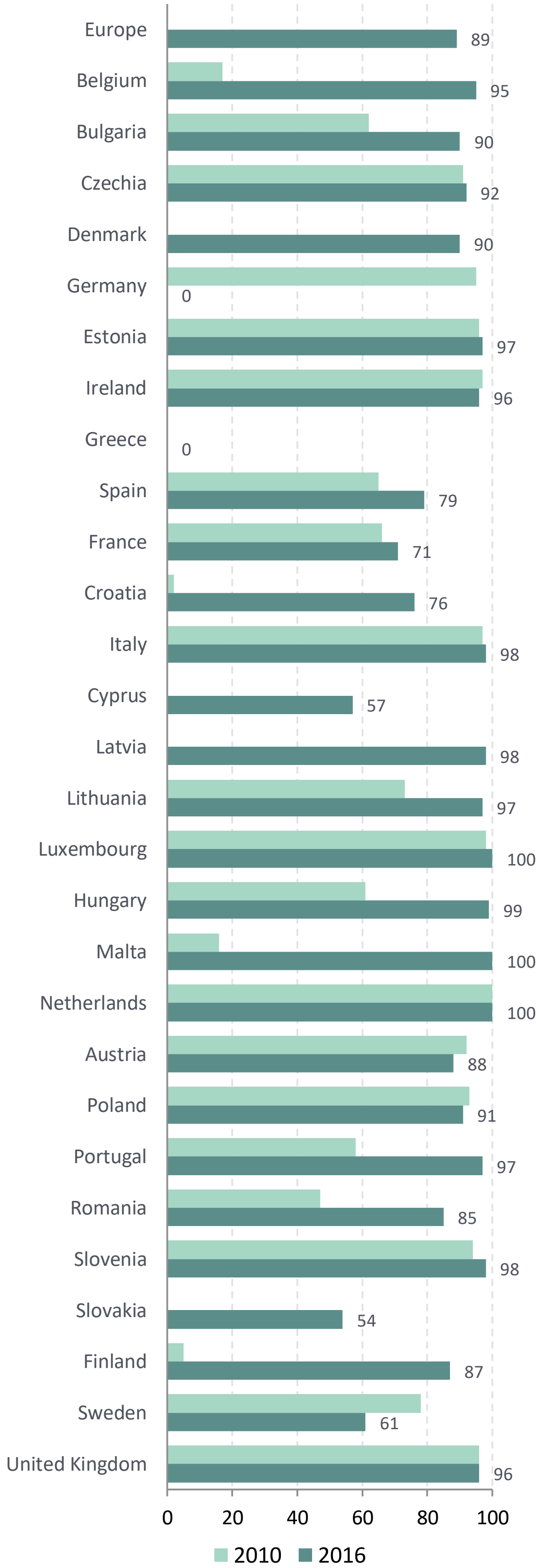


Figure 2.4.1 Recovery rate (EC,2019)

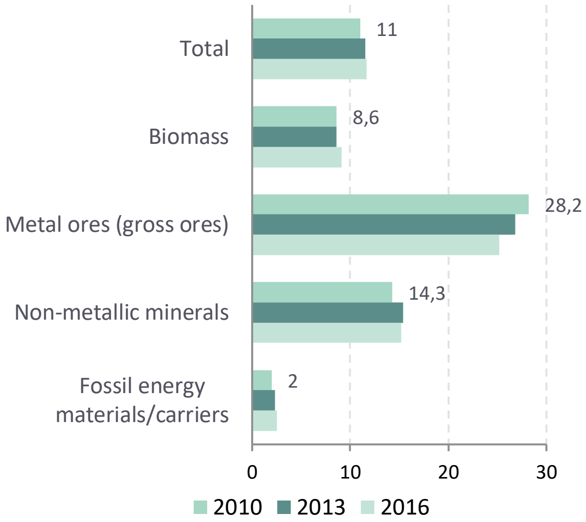


Figure 2.4.2 Circular material use rate by material category, Source: (EU, 2019)

standing highest and more than twice of Europe. This means the amount of secondary raw material as compared to primary raw material is high and avoids extraction of primary material (European Commission, 2018c). The other high scorers in CMU are Italy and France and 17.1% and 19.5% respectively.

11% of the material demand in EU was provided by the recycled materials in 2014. The CMU rates can be analyzed between 2010 and 2014 in four broad categories: biomass, metal ores, non-metallic minerals and fossil fuels as shown in **Figure 2.4.2**. CMU increased for non-metallic minerals between 2010 and 2014, jumping from 13.9 % to 15.2%.

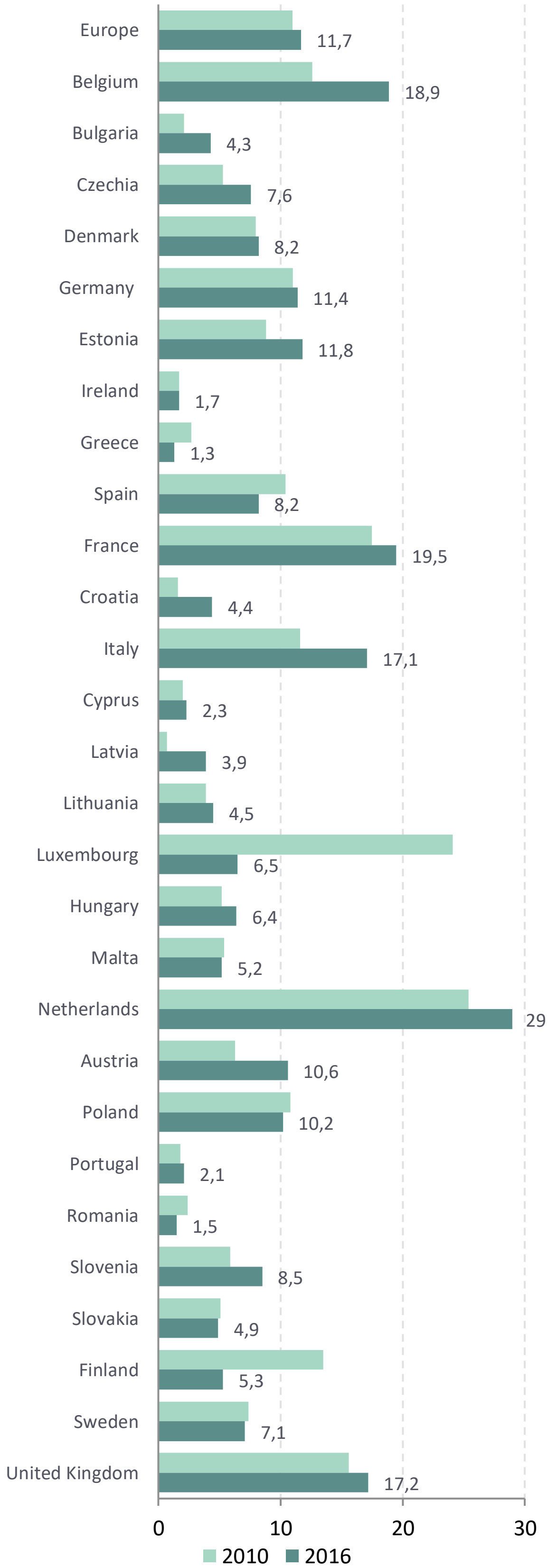


Figure 2.4.3 Circular Material Use rate, Source: (EU,2019)

2.5 Circularity Indicator for buildings

This section discusses various circular economy related indicators to measure and compare circularity between competitors via an aggregated value based on various aspects like design for disassembly, material re-use and combination of both.

2.5.1 Transformation Capacity

Transformation capacity is a knowledge model developed by Durmisevic to assess the disassembly potential of building, systems and products. This knowledge model is defined by two criteria, Independence and exchangeability of building elements. Independence is assessed by functional decomposition, systemization, base element specification, relational pattern and life cycle coordination. And Exchangeability is assessed by type of connections, assembly sequence and geometry of product edge. These can be called as Design for disassembly aspects which can be used to judge the transformation capacity of at "early design phase".

The detailed description of these aspects can be found in (Durmisevic, 2006), although these design for disassembly aspects are further classified in **Table 2.5.1**. The weightage of these determining factors on the Transformation capacity is illustrated in **Figure 2.5.1**.The grading method of these determining factors can be found in Appendix 1.

Design for Disassembly aspects	No.	Abbv.	Determining factors
1. Functional decomposition (FD)	1.1	fs	Functional separation
	1.2	fdp	Functional dependence
2. Systemization (SY)	2.1	st	Structure of material levels
	2.2	c	Type of clustering
3. Base element (BE)	3.1	b	Type of base element
4. Life cycle coordination (LCC)	4.1	ucl	Use life cycle coordination
	4.2	tcl	Technical life cycle coordination
	4.3	s	Coordination of life cycle and sizes
5. Relational pattern (RP)	5.1	r	Type of relational pattern
6. Assembly process (A)	6.1	ad	Assembly direction
	6.2	as	Assembly sequence
7. Geometry (G)	7.1	gp	Geometry of product edge
	7.2	spe	Standardization of product edge
8. Connection (C)	8.1	tc	Type of connection
	8.2	af	Accessibility of connection
	8.3	t	Tolerance
	8.4	mj	Morphology of joints

Table 2.5.1 List of DfD aspects and sub-aspects (Durmisevic, 2006)

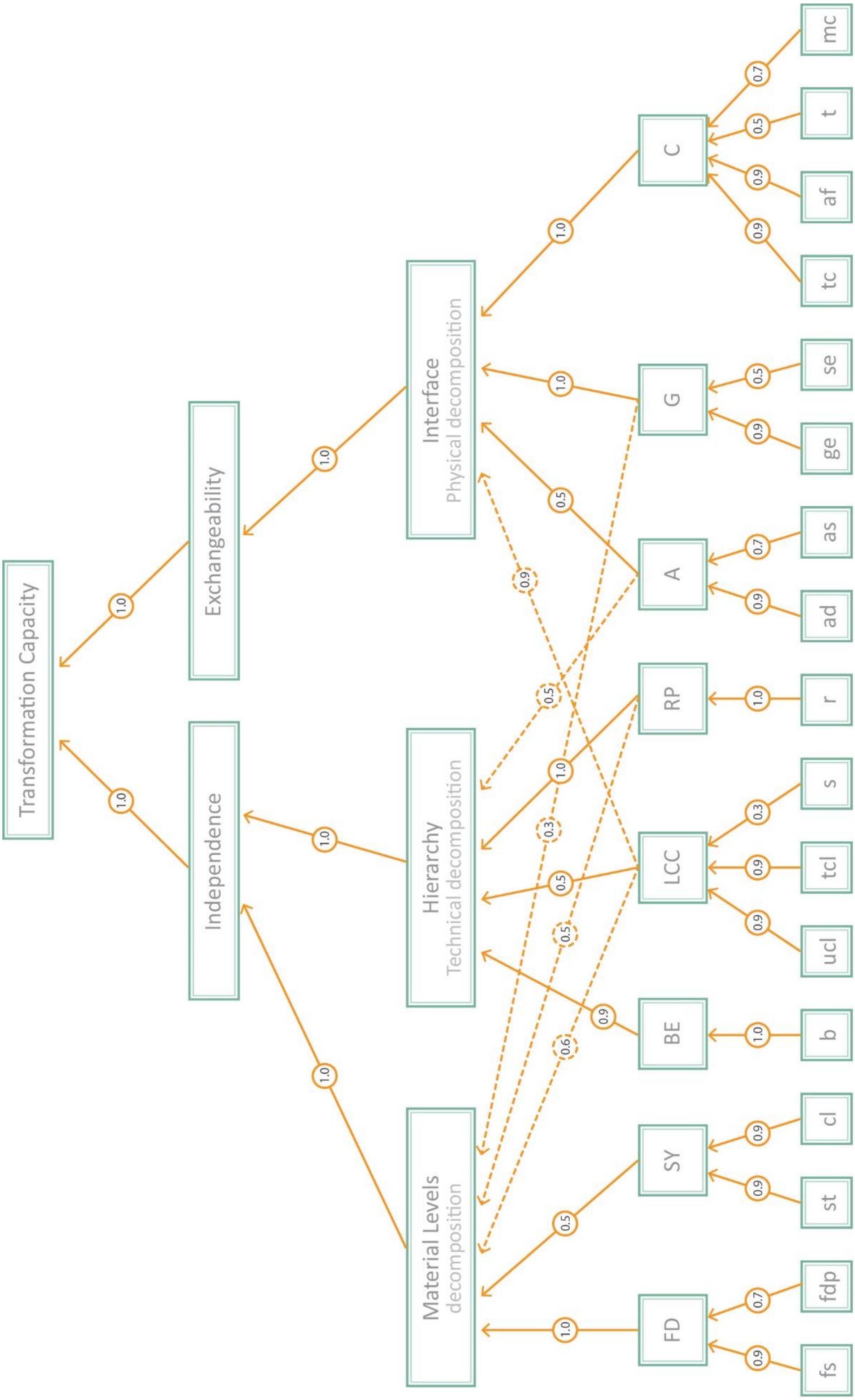


Figure 2.5.1 Transformation capacity and weighted factors (Durmisevic, 2006)

Relational diagram of various components in the assembly gives the insight about the transformation capability. It is also appropriate to have an intermediary element between components of varying life cycles to make transformation independent of one another and with least damage.

"The model is based on fuzzy input data that represent linguistic variables. Traditional linear models, which are based on correlation co-efficiency, have a high level of imprecision when dealing with such data. For this reason the model has been developed using fuzzy logic, which is more accurate when dealing with such data."(Durmisevic, 2006)

Traditional buildings are represented by a complex relational diagram, which means that the components are integrated with each other to form a dependent structure. Hence, replacement of any one component cannot be assured without demolition. The number of relation and its pattern influences the disassembly of structures. Durmisevic (2006) made a distinction of 6 types of assemblies as shown in **Figure 2.5.2**.

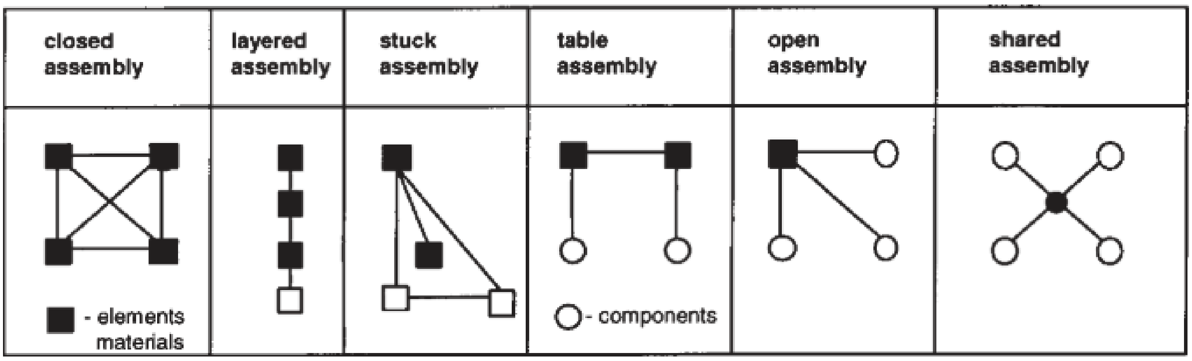


Figure 2.5.2 Types of assemblies based on relational pattern, Source: (Durmisevic,2006)

Buildings that are not systemized and are static represent the closed, layered and stuck assemblies. Whereas in buildings where components are kept independent from one another by creating dependent only relations within an assembly (such as a window) are represented by open hierarchies.

The relational diagram can represent relationship between different sub-assemblies. Where all subsystems can have relation with the load bearing system of the structure. In this way components that belong to subsystems can be replaced.

If all elements within a building are systemized in a column that correspond to a building functions and hierarchy of assembly then vertical relations would be relations within one functional group and horizontal relations represent the relations between different functional groups. This can be understood in **Figure 2.5.3**. If different functional groups have relations between them, that would mean difficulty in disassembly and is not ideal for transformation.

Graph database tools like NodeXL can be used to create such relational pattern or social network analysis of building components. This kind of information can be retrieved from a BIM already (Denis, De Temmerman, & Rammer, 2017b).

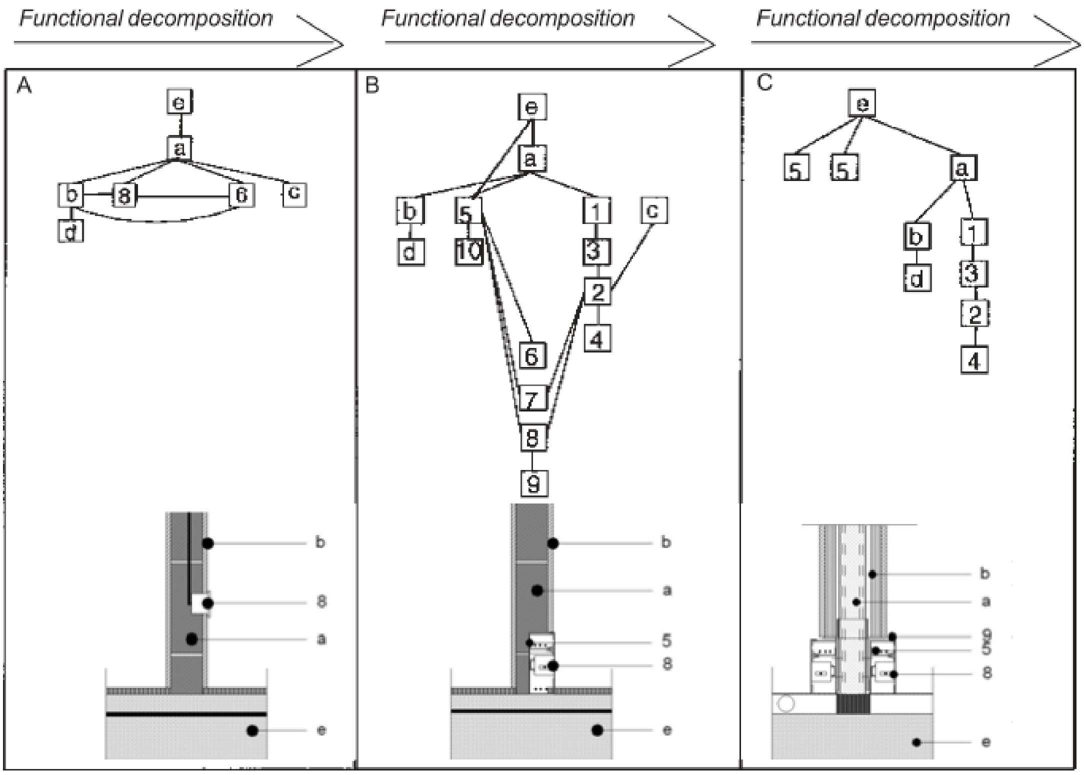


Figure 2.5.3 Relational pattern between different wall systems and its different functional groups, Source: (Durmisevic, 2006)

(Denis, De Temmerman, & Rammer, 2017a) studies the potential of such graph theories to understand buildings. It is proposed to look at buildings not as static finished product but as an assembly of elements and components linked together through different connections systems. (Denis et al., 2017b) discusses to combine Building information Modeling (BIM) and Design for Change (DfC) through tool development to optimize designers' decision making.

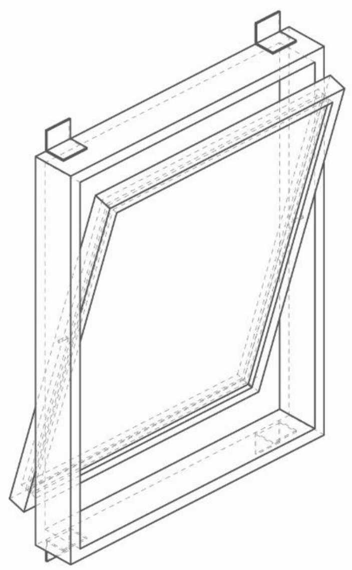


Figure 2.5.4 A simplified openable window, Source: Own illustration

Potential of relational pattern and social networks in analyzing the relationship between building components can be useful to determine the disassembly potential of a building system. Also, any building component such as an openable window (**Figure 2.5.4**) can be conceptually visualized as network of its individual element.

A relationship can be defined between different components with a DfD aspect such as 'type of connection'. As shown in **Figure 2.5.5**. This can inform how many components are independent of other components and whether it is easy to disassemble for repair, repurpose etc. In case of recycling at EOL, the joinery between components does not have to be flexible.

Other DfD aspects however are more difficult to be defined in graph database, such as, 'geometry of product edge'. Every element that come together to form a system has to be analyzed w.r.t 6 principle type of interfaces (as discussed in **Figure 2.3.3**). Due to the different shearing layers of the building such as structure, skin, service, space plan etc. it is complicated to define these parameters at early design phase. Different components come together to form a building.

Hence, it may be the case the two different components are assembled together to form a new component. For instance, a product C is made from component A & B. Even if the geometry of product edge is known for the individual component, there will be a different geometry edge of product C. Since, it depends on the engineering detail of the component, it is difficult to determine at early phase of design.

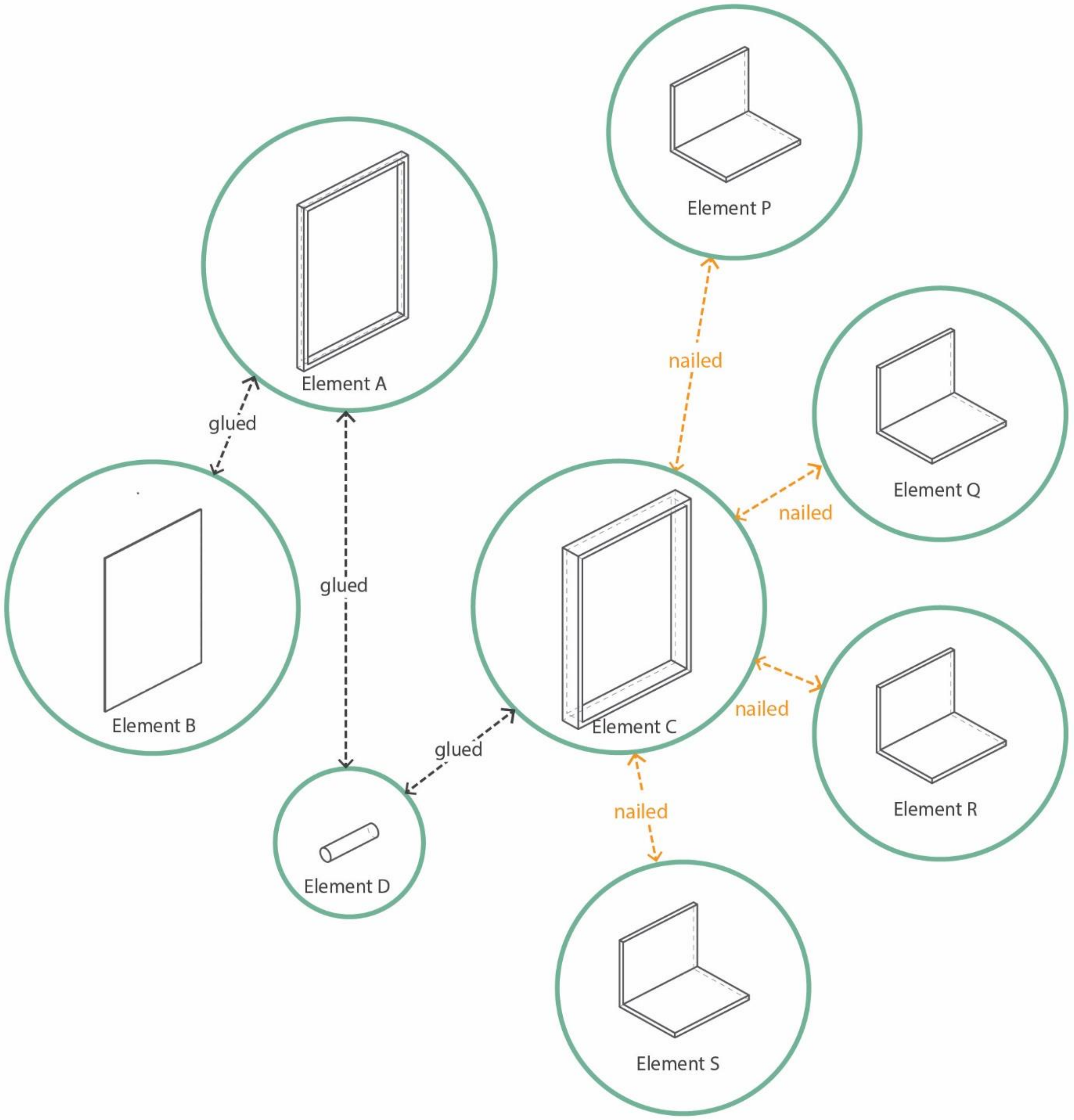


Figure 2.5.5 Relational diagram between different components of an openable window, Source: Own illustration

'Assembly and Disassembly sequence' is also important factor defining the transformation for adaptability in a building. This can be done by categorizing the components in 5 shearing layers of the building. In practice structure is assembled first and then skin, services etc. If NL/Sfb classification is used as one of the parameters of the label in material database, the probable assembly sequence can be visualized using data visualization platforms.

But, this methodology becomes complicated in case of adaptive reuse. For instance, an aluminum mullion will be classified as a window element according to NL/Sfb classification, but the same mullion might be fit to be used as a structural element for a small-scale project. This would mean that the assembly of the mullion would be in the beginning. Whereas through the classification methodology it would be treated as an element of the skin. To analyze the assembly sequence and hence transformability of the building, new classification needs to be given to the aluminum.

As discussed in section 2.7.2 if assembly sequence is analyzed with life expectancy of material, potential materials can be identified that needs replacement or material that have longer lifespan than the building must be demounted without damage. Using relational patterns several aspects of disassembly can be analyzed.

To analyze DfD aspects, life expectancy will be measured against density of different material in a graphical manner such as in **Figure 4.6.1**. This will be further discussed in section 5.2.4.

2.5.2 Building Circularity Indicator (BCI)

(Verberne, 2016) developed Building Circularity Indicator (BCI) which is build up from Material Circularity Indicator (MCI) and knowledge model for Transformation capacity by (Durmisevic, 2006). In **Figure 2.5.6** shows the hierarchy of calculations proposed by Verberne using the study of Durmisevic. But before explaining the BCI,

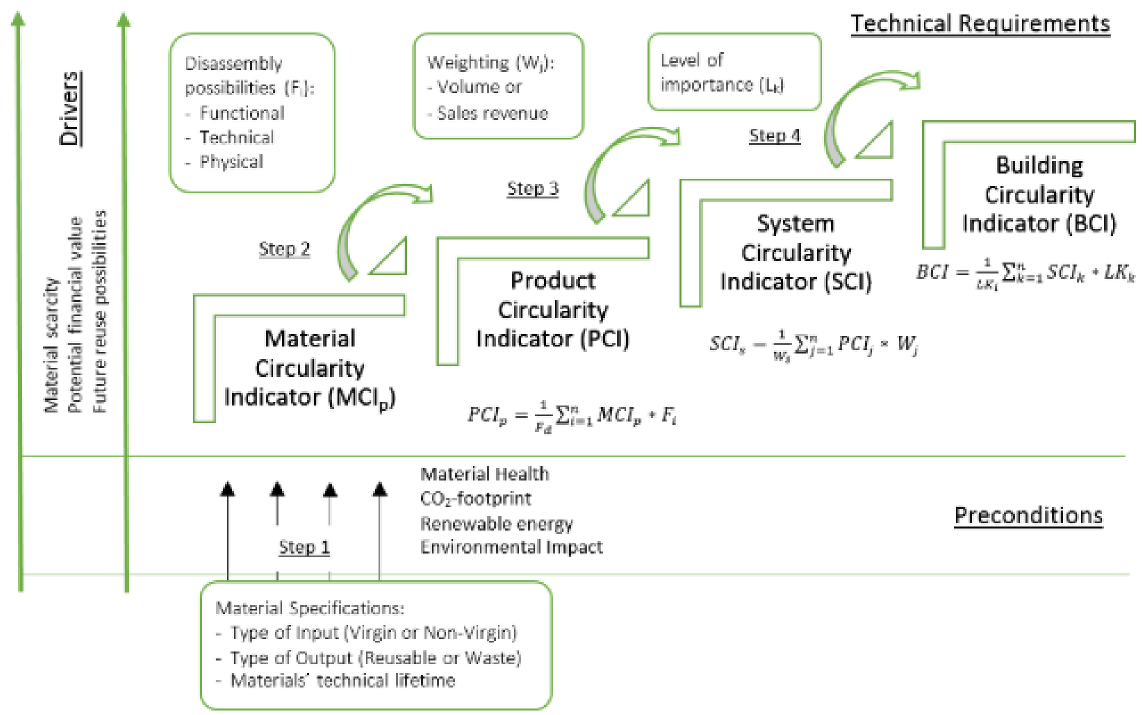


Figure 2.5.6 Building Circularity Indicator, Source: (Verberne, 2016)

BCI is calculated by the calculation of Material Circularity Indicator (MCI_p), Product Circularity Indicator (PCI_p) and System Circularity Indicator (SCI). The calculation of MCI is explained in the next section of this chapter. But, according to Verberne's interpretation of Utility X **(Eq.3)**, it is the ratio of life time of the product L_p and lifetime of the system L_{sys} it belongs to, for example, Site (500), Structure (100), Skin (20), Services (15), Space Plan (10) and stuff (5) defined by Brand (1994). Whereas, according to Ellen MacArthur Foundation & Granta Design, 2015 utility X **(Eq.2)** is the ratio of the length of product's use phase L and industry average length of use phase L_{av} or Functional units of the product U and Industry average functional unit U_{av}. One must choose either one of them, but not both. The utility encourages for building products of longer life-span. Increasing L with a fixed L_{av} will increase X and eventually increase the MCI value. Also, increase in L_{av} while the product that is being assessed has the same L, will decrease the MCI.

Whereas in Verberne's equation **(Eq.3)** L_{sys} is based on constant values of shearing layers of Brand (1994), any industrial advancement will not reflect in the MCI. Also L_p is different for different parts of the system, therefore product specific industry average value should be considered.

$$X = \left(\frac{L}{L_{av}}\right) \times \left(\frac{U}{U_{av}}\right) \qquad \textbf{(Eq.2)}$$

$$X = \left(\frac{L_p}{L_{sys}}\right) \qquad \textbf{(Eq.3)}$$

PCI_p is calculated by assessing the interfaces and connections between products and materials. This is calculated in order to ensure the circularity of a product for further re-use. In case of closed system approach where elements maybe chemically bonded, re-use or recycle of such products cannot be guaranteed. Therefore by using Design for Disassembly principles defined by Durmisevic, PCI_p is considered to be practical circularity value for a product whereas, MCI is considered as theoretical circularity value by Verberne.

To calculate PCI_p, Design for Disassembly aspects are used (see **Table 2.5.1**).

$$PCI_p = \frac{1}{F_d}\sum_{i=1}^{n} MCI_p \times F_i \qquad \textbf{(Eq.4)}$$

Where F_d is sum of all DfD aspects and F_i is one of the DfD aspect. DfD are not dependent on each other in this equation. Also (Verberne, 2016) states -

"The DDF are not dependent on each other in this situation, which means that each variable can cause the same amount of impact. In reality, this won't be the situation, but this assumption has been made since there isn't any research that makes such a distinction."

Whereas from the previous section we know that Durmisevic proposed the weightage of all the DfD aspects in the final Transformation capacity (see **Figure 2.5.1**). Also, Transformation capacity is determined by fuzzy variables which are a qualitative way of estimating the disassembly potential of any system. If Transformation capacity is lower than 0.6 percent, then design changes must be made in order to achieve high disassembly potential.

SCI is developed to assess the circularity of products by weight of sales revenues separated by system layers defined by Brand in 1994. **(Eq.5)**& **(Eq.6)** gives the theoretical and practical SCI respectively, as PCI_p is considered to be practical where disassembly potential is taken into account at material level.

$$SCI_{s(t)} = \frac{1}{W_s}\sum_{j=1}^{n} MCI_j \times W_j \qquad \textbf{(Eq.5)}$$

$$SCI_{s(p)} = \frac{1}{W_s} \sum_{j=1}^{n} PCI_j \times W_j$$ **(Eq.6)**

Where W_j is mass of the product j and W_s is summation of all product's mass.

Finally, BCI is calculated by **(Eq.7)**& **(Eq.8)**

$$BCI_{(t)} = \frac{1}{LK} \sum_{k=1}^{n} SCI_{(t)k} \times LK_k$$ **(Eq.7)**

$$BCI_{(p)} = \frac{1}{LK} \sum_{k=1}^{n} SCI_{(p)k} \times LK_k$$ **(Eq.8)**

Where $SCI_{(t)k}$is the theoretical value and $SCI_{(p)k}$ is practical value of SCI
$LK_k$is the factor for system dependency (see **Figure 2.5.7**)
LK is sum of the system dependencies

System dependency	Stuff	1.0
	Space plan	0.9
	Services	0.8
	Skin	0.7
	Structure	0.2
	Site	0.1

Figure 2.5.7 Fuzzy variables for various systems based on Brands shearing layers (Verberne, 2016)

The model of BCI is tested in (Disseldorp, 2018) while also adding additional steps to check the system and product health w.r.t NEN 2767 regulations and calling it Circular Redevelopment Potential Indicator.

Conclusion

BCI is developed as a management tool to measure circularity during the lifecycle of a building. It is not intended to be a certification or label for circularity. It is a means to have a standardized language between various contractors to differentiate themselves from competitors. There are two short-comings in this approach –

Firstly, the interpretation of Utility X is different from the utility equation proposed in Ellen MacArthur Foundation & Granta Design, 2015 (see **(Eq.2)**&**(Eq.3)**). Lifetime L of a product should directly relate with industrial average lifetime L_{av} of the similar product. According to Verberne's **(Eq.3)** the products with longer lifetime than the system will appear more circular in terms of material flow than they actually are and similarly the products with lower lifetime w.r.t to the system would appear less circular than they actually are. The motive of MCI is to keep the specific material or product in circular flow, as long as possible irrespective of which assembly it belongs to. But with Verberne's approach circularity is defined by the system it belongs to hence, there will be different circularity value if the product changes its system. Hence, it cannot be a standard way of assessing circularity of a product or comparing with other similar products.

Secondly, by multiplying MCI_p (which is a quantitative estimate of circularity of a product) with graded DfD factor F_i distorts the evaluation of MCI. In order to determine MCI we must know mass of -

- Reused content
- Recycled content
- Reusable content
- Recyclable content

Also,

- Recycled efficiency
- Recycling efficiency
- Lifetime of the product
- Industry average lifetime of the similar product

To determine these inputs, one has to assess the technical, physical and functional decomposition of the product first, rather than assuming these values in isolation. Also, there is a lack of a comprehensive validation case in Verberne, 2016 with all the factors of MCI considered. If the variables of MCI defined keeping in mind the disassembly potential of the product, then MCI is enough to assess the flow of materials. Even if MCI variables are defined in Verberne's model at material level, it gives imprecise or no information regarding the actual reusable, recyclable mass of the product. This can be seen as a proof in Disseldorp, 2018 where Wouter uses Technical lifetime (L_{sys}) of all products in 'The Green House' as 15 years (as the building was ought to be dismantled in 15 years, and not as industry average) and functional lifetime ($L_p L_{sys}$) as product's actual estimated life. He achieved higher circularity (close to 1) values for all the components that were used in the building. Hence, it is most ideal to use MCI from Ellen MacArthur Foundation & Granta Design as they describe.

2.5.3 Alba concepts

Alba concept developed its Product Circularity Index (PCI) based on origin of material, waste scenario, technical lifespan and volume of materials called as Material index (M) combined with Releasability index (Li) based on Connection type, Accessibility connection. Similarly, Element Circularity Index (ECI) and Building circularity Index (BCI) is developed. From thesis study of Wouter, it can be inferred that Alba concepts use MCI (utility X interpretation) the same way Wouter and Verberne used. Although there is no literature available for the calculation of BCI or support the argument.

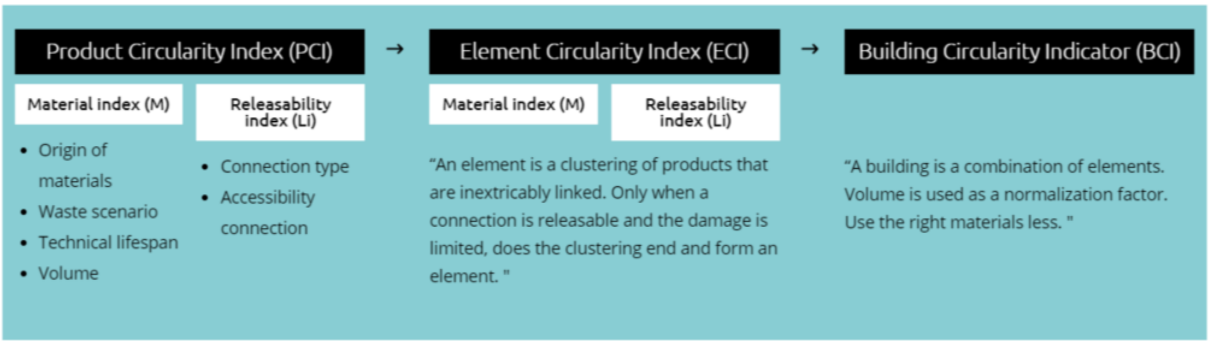


Figure 2.5.8 Building Circularity Index by Alba concepts

2.6 Product level circularity indicators

2.6.1 Material Circularity Indicator

Material circularity indicator (MCI) is a commercially available web-based tool that lets businesses measure the circularity of their product to fit a circular economy-based business model. LCA derives the environmental impacts throughout the life cycle of a product whereas MCI focuses on the material flow throughout the use of the product. It has been developed by Ellen MacArthur Foundation and Granta Design integrated with the MI:Product intelligence package. By calculating the mass of virgin material, unrecoverable waste, Linear Flor Index and utility of a product, a rating from 0-1 can be given to the product, where 0 depicts that the product is linear and 1 would mean there is no waste or no use of virgin material. MCI does not consider what material is used, its scarcity, toxicity, embodied energy, water footprint and cost of the product which might be essential in decision making in some industries. Hence it is advised to use other existing complementary calculators with MCI (www.ellenmacarthurfoundation.org, 2017).

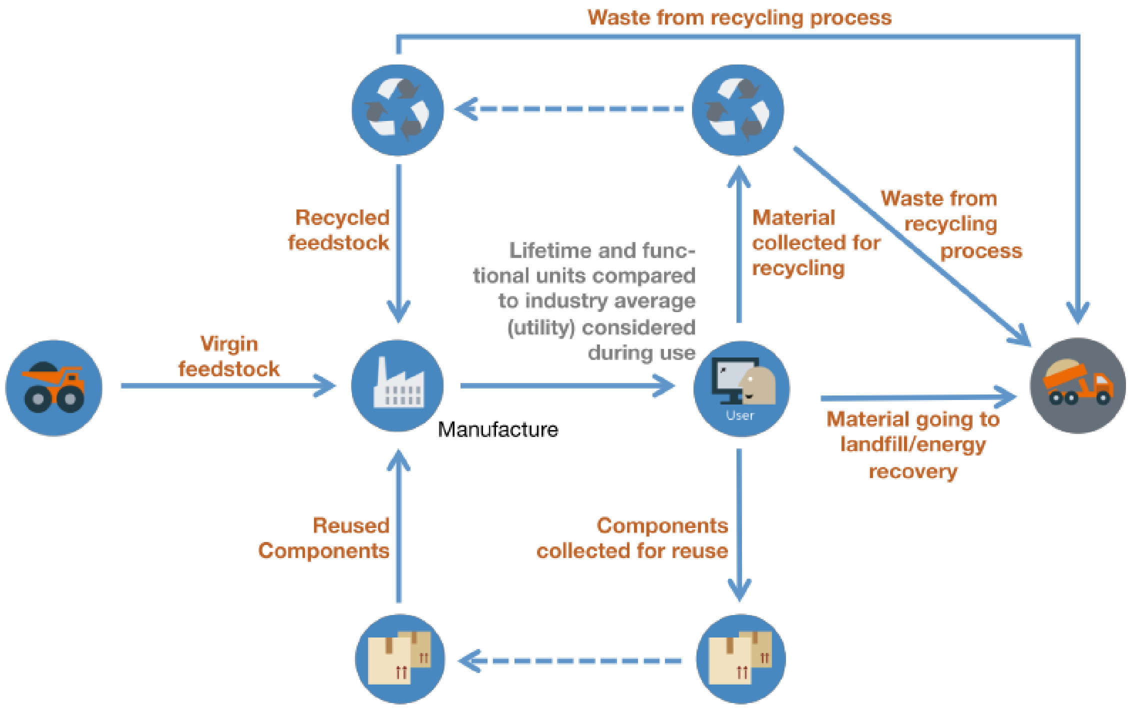


Figure 2.6.1 Diagrammatic representation of material flows (Ellen MacArthur Foundation & Granta Design, 2015)

Calculating Virgin Feedstock

Virgin mass V can be calculated by determining fraction of recycled content F_R and fraction of reused content F_u

$$V = M(1 - F_R - F_u) \quad \textbf{(Eq.9)}$$

Where M is the total mass of the component.

Calculating Unrecoverable waste

To calculate total unrecoverable waste W we need to calculate the amount of material that goes to landfill or energy recovery W_O after a lifecycle (W_O), waste generated due to recycled content used as feedstock (W_F) and waste that will be generated in the recycling process (W_C) after one lifecycle.

W_O can be calculated using **(Eq.10)** where C_R is fraction of material that goes for recycling and C_U is fraction that can be reused either in the same product or anywhere else.

W_F can be calculated using **(Eq.12)** where E_F is the efficiency of the recycling process used.

W_C can be calculated using **(Eq.12)** where E_c is the efficiency of the recycling process that will be used after the lifecycle.

And finally, total unrecoverable waste W is calculated using **(Eq.13)**. Detailed explanation of using ½ of the sum of W_C & W_F is mentioned in Ellen MacArthur Foundation & Granta Design, 2015.

$$W_O = M(1 - C_R - C_U) \quad \textbf{(Eq.10)}$$

$$W_F = M\frac{(1 - E_F)F_R}{E_F} \quad \textbf{(Eq.11)}$$

$$W_C = M(1 - E_c)C_r \quad \textbf{(Eq.12)}$$

$$W = W_O + \frac{W_F + W_C}{2} \quad \textbf{(Eq.13)}$$

Calculating Linear Flow Index

Linear Flow Index LFI measures how much material is ending in linear fashion, where virgin materials are sourced and end up in landfill. This can be calculated using **(Eq.14)**.

$$LFI = \frac{V + W}{2M + \frac{W_F - W_C}{2}} \quad \textbf{(Eq.14)}$$

Calculating Utility

Utility of a product can be defined in two ways, either by the length of products use phase (lifetime) or functional units. If the lifetime L of a product is longer or shorter than the industry average L_{av} in a given amount of time then L/L_{av} accounts for reduction or increase in the waste stream. If the lifetime L of a product is doubled, the waste created, and the virgin material used per year by the linear portion of the products flow is halved. In the same way if lifetime was half of the industry average, the waste and virgin material used per year would double. The same is true for functional unit U and industry average U_{av}.

"It is expected that in most cases either lifetimes or functional units, but not both, will be used to calculate X. If lifetimes are used exclusively, this means assuming that U/U_{av} = 1. If functional units are used exclusively, this means assuming that L/L_{av}= 1."(Ellen MacArthur Foundation & Granta Design, 2015)

$$X = \left(\frac{L}{L_{av}}\right) \times \left(\frac{U}{U_{av}}\right) \quad \textbf{(Eq.15)}$$

"Whilst the methodology may be used in a 'what if' mode to guide product design, design data should not be used in calculating the MCI of an actual product. For example, a product may be 100% recyclable, but actual recycling rates should be used in the calculations. Or, in the case of a product that is designed for a longer life than – for whatever reason – the actual product experiences in practice, the actual lifetime should be used in the calculations, not the lifetime the product is designed for."(Ellen MacArthur Foundation & Granta Design, 2015)

Calculating Material Circularity Indicator

The Material Circularity Indicator can be calculated using **(Eq.16)** where $F(X)$ is the utility factor (see **(Eq.18)**).

"However, given the definition of the function F (Equation 2.12 below), this value can be negative for products with mainly linear flows ($LFI \approx 1$) and a utility worse than an average product (X <1). To avoid this, the Material Circularity Indicator is …" using **(Eq.17)** where MCI_p will give a value from 0 to 1. Using this method two very linear products cannot be compared because one might have more negative value than other. It is assumed that this methodology will not be used to assess such products.

$$MCI^*_P = 1 - LFI \times F(X) \quad \textbf{(Eq.16)}$$

$$MCI_p = \max\left(0, MCI^*_p\right) \quad \textbf{(Eq.17)}$$

$$F(X) = \frac{0.9}{X} \quad \textbf{(Eq.18)}$$

2.6.2 Swan Ecolabel

Swan criteria ensure appropriate quality and durability of goods. Use of secondary raw material for products and packaging is noted. Aspects of recyclability, separability is considered while limiting the use of hazardous chemicals which may hinder this process later (Suikkanen, Nissinen, & Ari, 2017). The focus of Swan is to

a) Setting strict energy requirements,
b) Minimizing chemical substances harmful to health and environment,
c) Promoting products that are resource efficient and,
d) Ensuring biodiversity protection by credible certification schemes.

To assess product circularity, Swan also considers MCI as a usual starting point. Circular economy is about ensuring material are kept in circulation as long as possible before ending up in landfill or recycling. This is done by assessing-

1. Product Service Time Extension, and
    a. Durability and Quality Requirements
    b. Upgrade and Repair
    c. Multi-functionality
2. Material circulation
    a. Secondary Raw Material
    b. Recycling and Recyclability

Detailed description of these assessment criteria can be found in project group guidelines, for example, Nordic Ecolabeling for Windows and Exterior doors, Version 4.8 March 2014-31 March 2022 (Ecolabelling, 2014). Although, secondary raw material only sets guidelines for the minimum fraction of recycled content required at material level. The circular flow of material is then assured by guidelines w.r.t to durability, reparability and finally recycling.

2.6.3 LEED

LEED stands for Leadership in Energy and Environmental Design which is a third-party green building certification program by U.S. Green Building Council (USGBC). It is an internationally renowned certification system that symbolize excellence in design, construction, and operation of high-performance green buildings and neighborhoods. It motivates the stakeholders to adopt sustainable building and community development voluntarily, consensus based, and market driven. LEED is applicable at any stage of the life-cycle of a building including new construction, ongoing operations, maintenance of existing building and retrofit to commercial building. The rating system is continuously being updated to respond to new technologies and policies. In this way yesterday's innovation becomes a standard practice of today (Green Building Council, n.d.).

(USGBC, 2019) describes the assessment criteria to assign certification on four different levels namely-Certified, Silver, Gold and Platinum. These criteria are broadly divided into 9 categories which have different weightage in the total score as shown in **Figure 2.6.2**. In total 110 credits can be achieved. If the total count of the achieved credit is 40-49 then the building will be called Certified; 50-59 credits is required for Silver certification, 60-79 is required for Gold certification and 80+ is required for Platinum certification.

Material and resources category forms about 10% or 14 out of the credits compared Energy efficiency which is the dominating of all with a weight of 33 credits. **Figure 2.6.3** shows sub-categories under Materials and Resources. Building Life-Cycle impact reduction accounts for 6 credits which can be achieved by one of the four options defined in (USGBC, 2019).

If 25%-75% of the surface area including structural elements, enclosure materials and permanently installed interior elements are re-used either on site or off-site then, 2-5 credits can be obtained. If Whole-Building Life-Cycle Assessment is conducted which demonstrates 5-20% reduction in at least 3 of the listed environmental impact categories, one of which should be GWP, then 2-4 credits can be obtained.

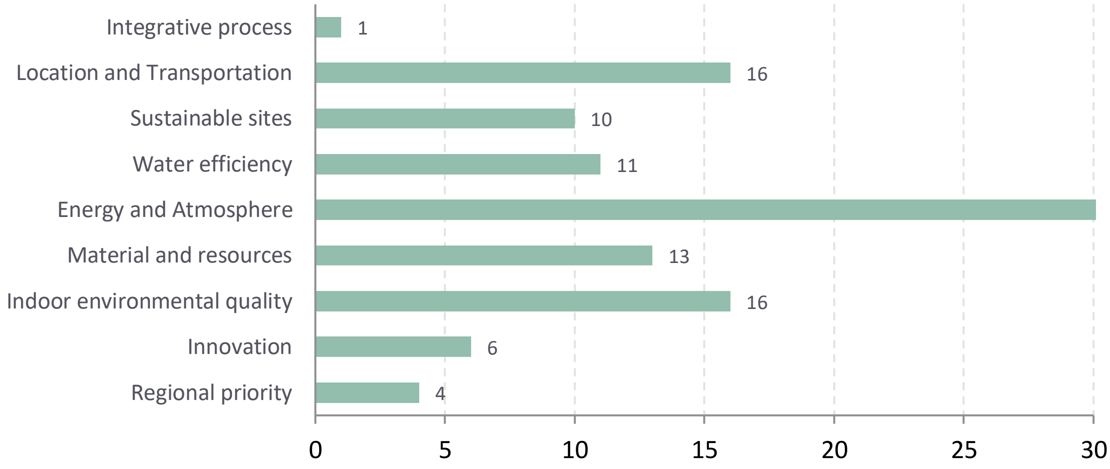


Figure 2.6.2 LEED v4.1 BD+C Scoreboard credit distribution (own interpretation)

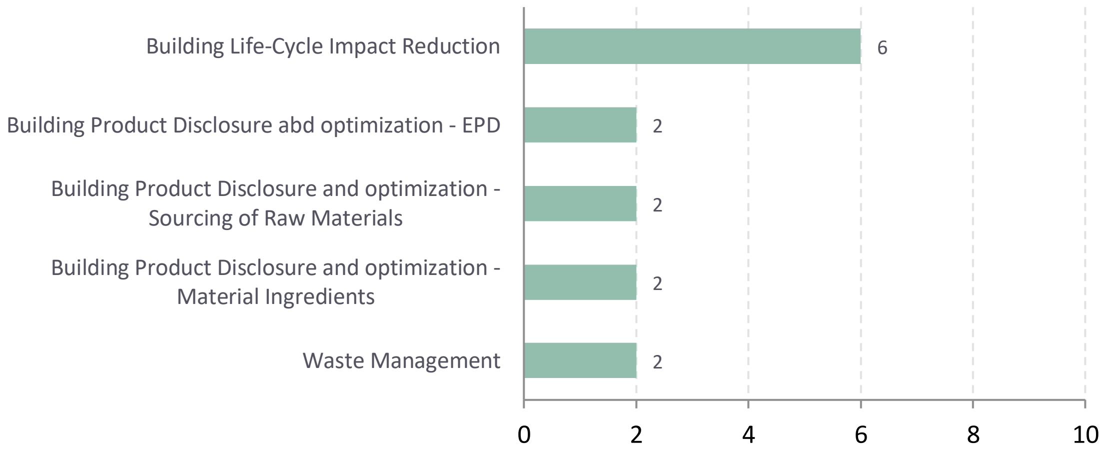


Figure 2.6.3 Material and Resources sub-categories credit distribution, LEED v4.1 BD+C Scoreboard (own interpretation)

2.6.4 Environmental impacts

A lot of existing Life Cycle Assessment (LCA) databases were developed after the release of environmental management standards UNE-EN ISO 14040 and UNE-EN ISO 14044 in 2006. But there are lot of variations between different databases because of the geographical locations of the studies and production standards. Also, there is lack of transparency of different studies. Hence, Martínez-Rocamora, Solís-Guzmán, & Marrero, 2016 in their paper stresses on the importance of choosing appropriate database of different origins, to achieve a more appropriate results.

(Kim & Azari, 2012) describes the way to estimate environmental impacts of a Curtain wall system following the ISO 14044. The author compares a wood v/s steel v/s Aluminum profile with the same overall size, configuration of vertical and horizontal divisions that would perform similar thermal requirements. The boundary condition for Timer curtain wall was defined as shown in **Figure 2.6.4**.

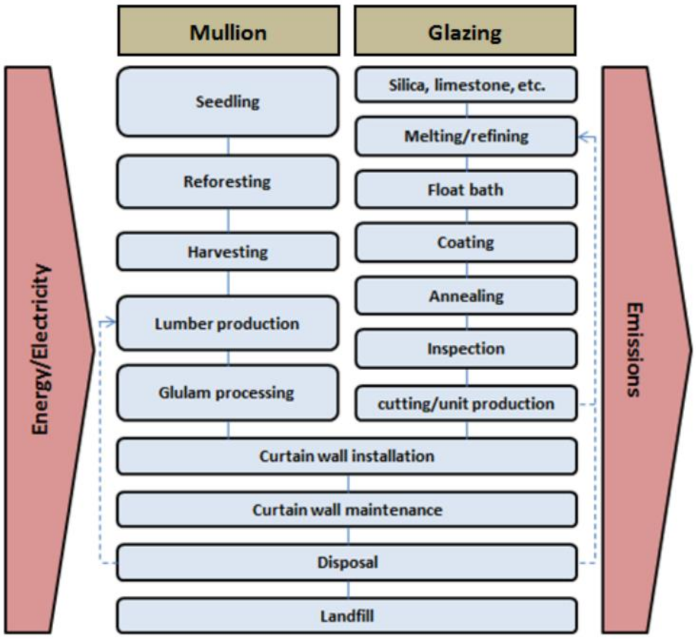


Figure 2.6.4 LCA boundary conditions for Timber curtain wall **(Kim & Azari, 2012)**

(Walker, Coleman, Hodgson, Collins, & Brimacombe, 2018) studies the measurement of material circularity with a life-cycle footprint tool based on LCA principles with a focus on material recovery and lifetime extension. Five scenarios of material efficiency were tested to assess the environmental benefits of recovery and reuse of materials from the supply-chain and at EOL by calculating the carbon footprint. The study only provides output in terms of CO_2 emissions which was considered sufficient to meet the goals of the study. Although a full LCA can provide a broader set of outputs in environmental impact categories such as Global Warming Potential, Ozone Depletion Potential etc.

(Zabalza Bribián, Aranda Usón, & Scarpellini, 2009) describes the simplified LCA methodology as complement for building certification. The impact category selected to perform the LCA study should be simple to understand by an architect, engineer and final users. Also, the category selected should complement the results of energy certification. Hence, embodied energy and CO_2 is considered. **Figure 2.6.6** describes the life-cycle stages considered in the complete LCA study of building. The stages that have lower impact on primary energy and CO_2 emissions are excluded.

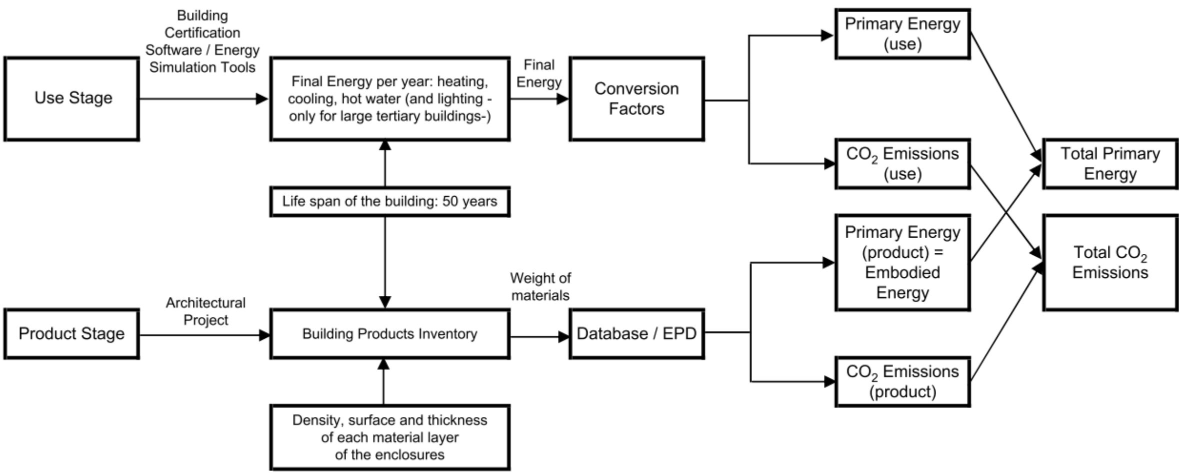


Figure 2.6.5 General structure of simplified LCA methodology proposed by (Zabalza Bribián et al., 2009)

Figure 2.6.5 shows the simplified stages in a complete lifecycle of a building and the stages that represented lower impact on embodied energy and CO_2 emissions were neglected. Total weight of all the building material was calculated by multiplying the density, surface area and thickness of various materials. It is also recommended to select a database whose inventory represent the real value of the region where the building is located. EPD's of the building materials can also be used in this case.

Stage	Module	Simplified LCA methodology: stages included
Product stage	Raw materials supply	Yes
	Transport	Yes
	Manufacturing	Yes
Construction process stage	Transport	No
	Construction-installation on-site processes	No
Use stage	Maintenance	No
	Repair and replacement	No
	Refurbishment	No
	Operational energy use: heating, cooling, hot water (and lighting – only for large tertiary buildings)	Yes
	Operational water use	No
End-of-life stage	Deconstruction	No
	Transport	No
	Recycling/re-use	No
	Disposal	No

Figure 2.6.6 Life cycle stages of a building and simplified LCA methodology, Source: (Zabalza Bribián et al., 2009)

It was found that embodied energy in products accounted for 31% of the total energy requirement during the lifespan of the building. And 41% of total CO_2 emissions were due to the building material such as doors, windows, roof, wall and foundation. In summary, this thesis is focused on environmental impacts at product stage, hence, general structure proposed by (Zabalza Bribián et al., 2009) for product stage is enough to make decisions at early design stage. Although, it is recommended to run energy simulation on a suitable software to complement the results.

The inputs required to measure MCI are also required for LCA and can be used to calculate the embodied CO_2. The first step is to set the goal and scope of the assessment, including relevant cycle stages and appropriate boundaries (Valencia, 2017).

2.7 Conclusion

MCI is developed as a general tool to indicate the linear flow of materials. It designed keeping in mind that any type of product can be assessed if the variables are known. (Ellen MacArthur Foundation & Granta Design, 2015) demonstrates the calculation of MCI using washing machine and power drills, which are electrical equipment.

In order to understand the concept of Material Circularity Indicator for building products a simulation was prepared to analyze MCI of a simple wall and window arrangement. The MCI of this arrangement is affected by the joinery between wall and window. Three types of joinery are distinguished to understand the effect. The three different cases are shown in **Figure 2.7.1**.

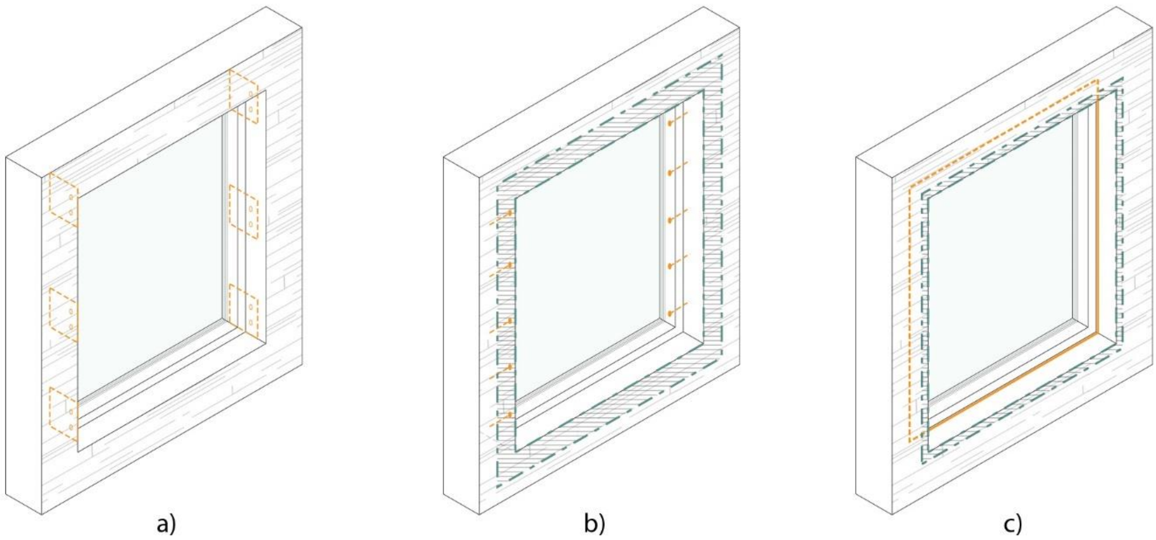


Figure 2.7.1 Three types to joinery between wall and window, a) fixed with demountable metal, b) Fixed with nails & c) Fixed with chemical, source: own illustration

Affected areas	**Type of joinery**		
	a) demountable-metal	b) Fixed with nails	c) Fixed with chemical joint
Expected wall thickness to be demolished at EOL (mm)	0	230	115

Table 2.7.1 Affected area of wall with respect to joinery

If the waste created in the wall due to fixed joinery ends up in landfill after disassembly. Two type of walls are analyzed, brick and concrete. This is mainly to understand the impact of mass on the circularity score. Also, both wall and window are considered as 100% reused. But, at the reusability and recyclability potential of the window is 0, whereas undamaged part of the wall is considered reusable.

MCI variables	Wall-Window	Wall	Window		Joinery
			Glass	Mullion	b) Fixed with nails
Material		concrete	Low-e glass	wood	steel
Mass (kg)	865	745	82	11	26
Virgin content	0.03	0	0	0	1
Reused content	0.96	1	1	1	0
Recycled content	0	0	0	0	0
Reusable content	0.84	0.98	0	0	0
Recyclable content	0	0	0	0	0
Unrecoverable waste (kg)	137	28	82	11	26
Utility	1	1	1	1	1
LFI	0.04	0.02	0.5	0.5	1
MCI	0.96	0.98	0.45	0.45	0

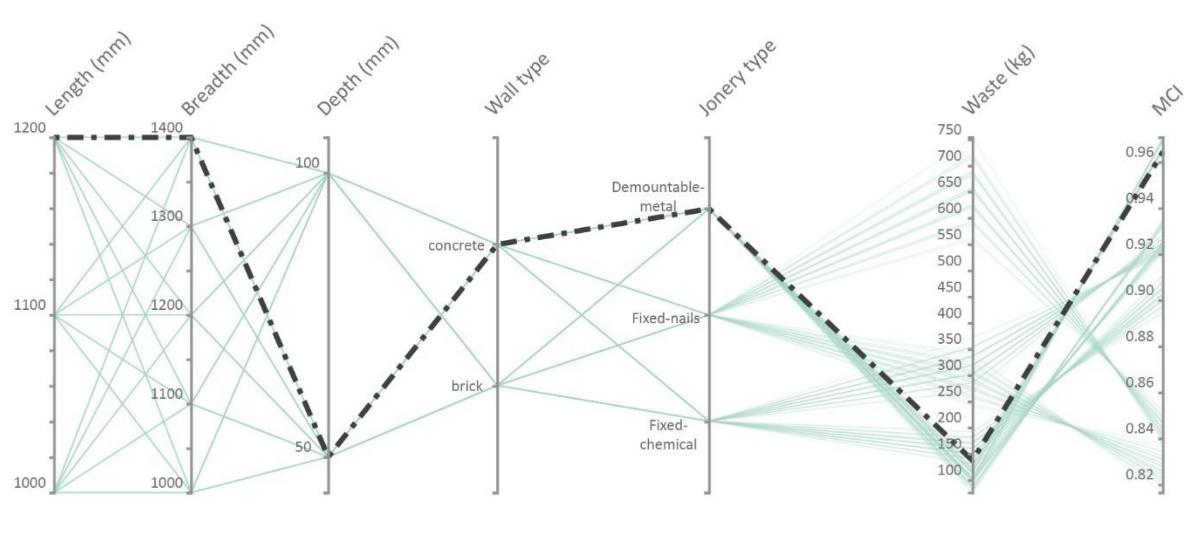


Figure 2.7.2 MCI calculation when demountable-metal joinery used between wall and window.

MCI variables	Wall-Window	Wall	Window		Joinery
			Glass	Mullion	b) Fixed with nails
Material		Brick	Low-e glass	wood	steel
Mass (kg)	865	745	82	11	26
Virgin content	0.03	0	0	0	1
Reused content	0.96	1	1	1	0
Recycled content	0	0	0	0	0
Reusable content	0.84	0.98	0	0	0
Recyclable content	0	0	0	0	0
Unrecoverable waste (kg)	754	660	82	11	0.34
Utility	1	1	1	1	1
LFI	0.18	0.02	0.5	0.5	1
MCI	0.83	0.98	0.45	0.45	0

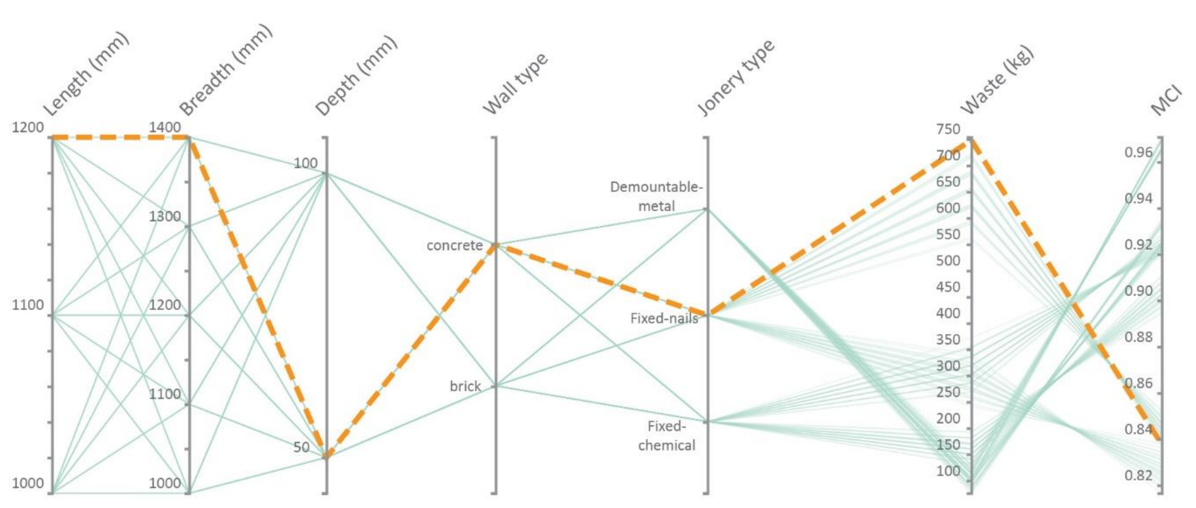


Figure 2.7.3 MCI calculation when nailing is used between wall and window.

MCI variables	Wall-Window	Wall	Window		Joinery
			Glass	Mullion	c) Fixed with chemical
Material		Brick	Low-e glass	wood	silicon
Mass (kg)	865	745	82	11	26
Virgin content	0.03	0	0	0	1
Reused content	0.96	1	1	1	0
Recycled content	0	0	0	0	0
Reusable content	0.84	0.98	0	0	0
Recyclable content	0	0	0	0	0
Unrecoverable waste (kg)	382.6	287	82	11	2.6
Utility	1	1	1	1	1
LFI	0.09	0.02	0.5	0.5	1
MCI	0.92	0.98	0.45	0.45	0

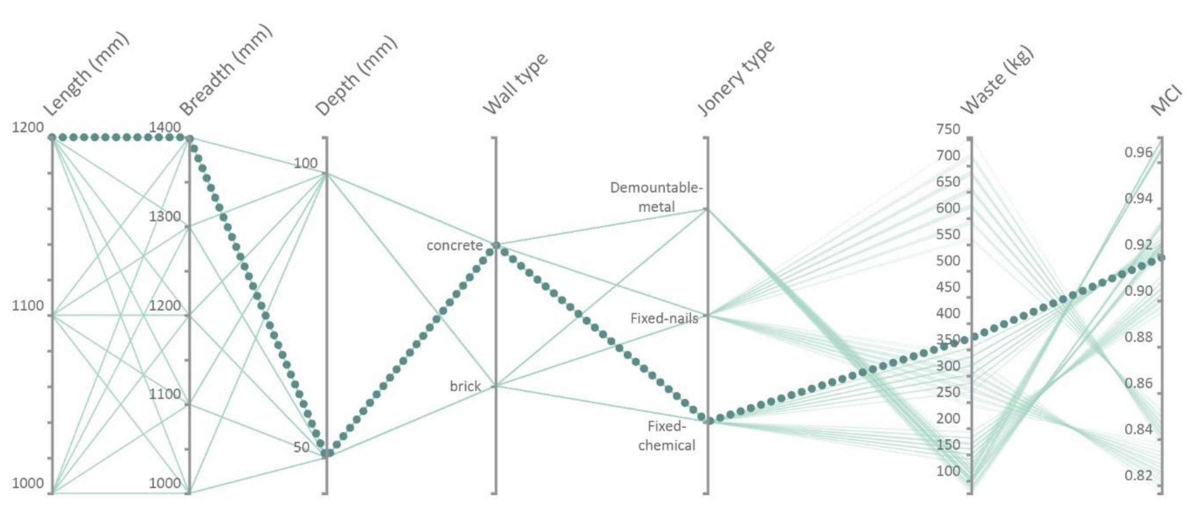


Figure 2.7.4 MCI calculation when chemical joinery is used between wall and window

From **Figure 2.7.2**, **Figure 2.7.3** & **Figure 2.7.4** it can be seen that the MCI value is higher when there is no waste created at the EOL. Also, the impact of circularity of wall played an important role in determining the MCI of the overall system. The MCI of window is same in all the cases and is nearly half of the MCI of the wall. But due to the fact that the mass of window is marginal compared to the wall, it has negligible impact on the MCI. As we can see in all three cases, window ends up as unrecoverable waste, and still the MCI is higher.

If we use the weighted factor as used by (Verberne, 2016), to set importance of structure lower and window higher (**Figure 2.5.7**) , then the MCI value will be as shown in Table 2.7.2.

	Wall-Window	Wall	Window
Weighted factor		0.2	0.7
MCI before weighted factors	0.96	0.98	0.45
BCI after weighted factors	0.60	0.196	0.35

Table 2.7.2 MCI values after multiplying with weighted factors from (Verberne, 2016)

BCI will ignore the amount of waste created by the concrete or brick and indicates a Circularity value is dominated by the Linear Flow Index LFI which depends on the waste generated after the use of the product. This factor keeps the scope for careful use of a product. Hence, there has to be a predefined value of extra waste that will be generated in disassembling a product. For example, a window needs to be taken out from a brick wall. This window at its component level is highly circular whereas the wall at its component level is less circular based on the waste that will be generated while taking the brick apart. But based on the joinery between the wall and the window there is going to be a waste at EOL (as illustrated in this section before). This can be called Indirect waste.

Calculating MCI of a product in isolation does not consider the future assembly. The MCI rating of a product while designing or procuring will be different after that product is placed in a building. Using DfD aspects MCI can be re-evaluated after assembly.

When a product reaches at the end of its use lifecycle, then either it can be recycled, keep re-using or divide into its constituents (if they can be used separately) and supply again. Landfill would mean 0 MCI. If all building elements are analyzed at its constituent level, meaning instead of determining MCI of the window (or any other component), calculating MCI of its individual components would ensure reusability of all components until the end of their life.

2.7.1 How does circularity affect environmental impacts?

Circular economy proposes to keep materials in continuous flow by reusing or recycling as compared to linear economy where the material ends up in landfill due to demolition. For keeping this continuous flow of materials, products need to be designed in such a way that individual components can be recovered fully for reuse or recycle. Current way of LCA is based on the linear economy where building components are fabricated in known factories and transported to the project site.

The LCA database that is available for calculating the environmental impacts of any product is based on industry standard manufacturing process, where a product is generally designed for one function. And after it can no longer serve that function, it is discarded for landfill. In case of circularly flowing material we need to additionally consider environmental impacts generated due to maintenance of a product after each lifecycle. This should then be compared with a product that ends up in landfill or recovery. Circularity is aimed to lower the overall environmental impacts that are generated when we extract virgin materials and that material ends up in landfill sooner than it should have.

Combined efforts to re-use secondary material and designing for disassembly would lower the negative environmental impacts. **Figure 2.7.5** shows the boundaries of the system to estimate embodied CO_2 per life cycle of a product whether it is new or secondary or combination of both.

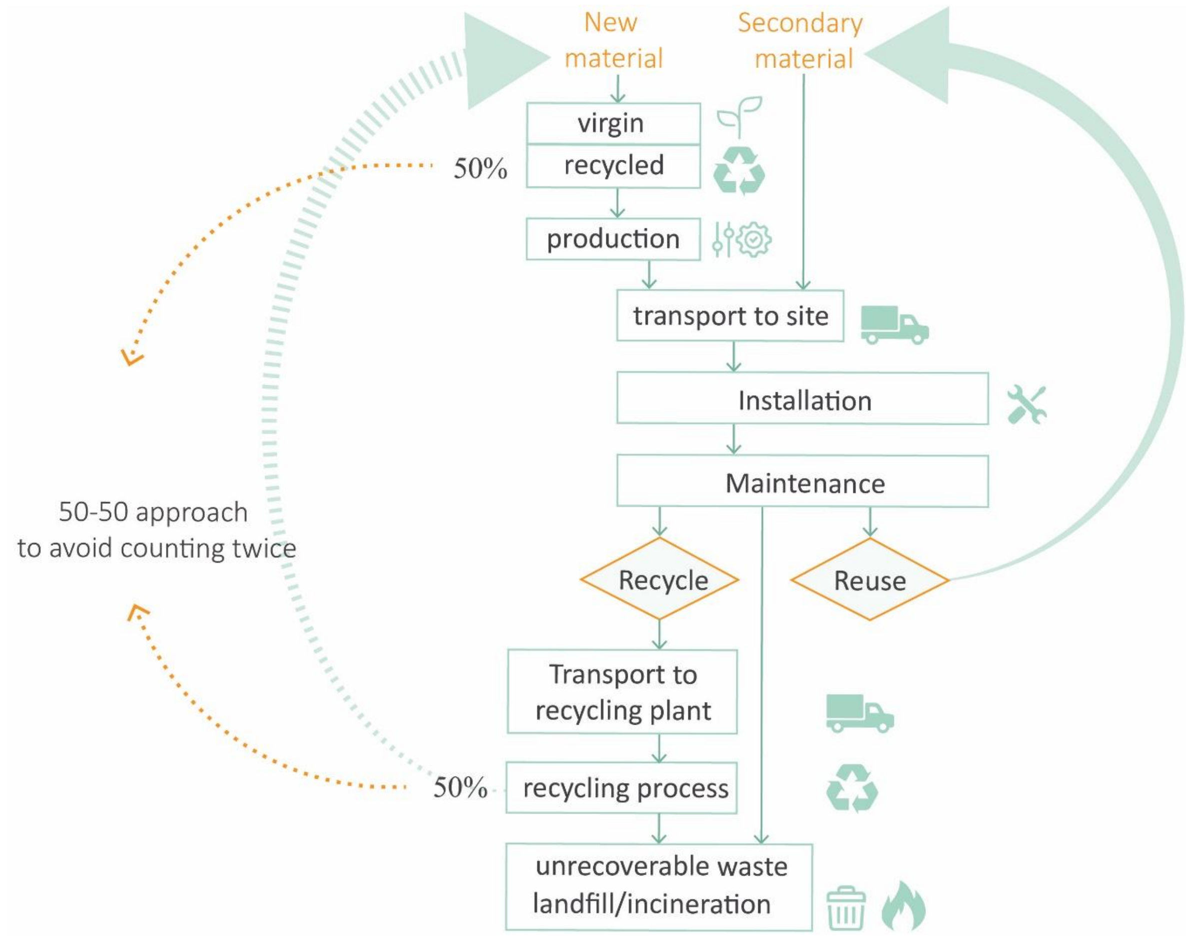


Figure 2.7.5 Boundary conditions to determine Embodied CO_2 per use life of a building material

For simplification and easy assessment with the limited data, life cycle stages that are included in the assessment are shown in **Table 2.7.3**.

Stage	Module	Stages included in the Assessment of embodied CO_2 of new material	Stages included in the Assessment of embodied CO_2 of secondary material (direct reuse)
1	Virgin and Recycled content	yes	no
2	Manufacturing	no	no
3	Transport to site	yes	yes
4	Installation	no	no
5	Maintenance	no	no
6	Transport to recycling plant	yes	yes
7	Recycling	yes	yes
8	Landfill/incineration	yes	yes

Table 2.7.3 Considered life cycle stages of new or secondary material in assessment of embodied CO_2

To calculate the CO_2 emissions in the recycling process, drawing from MCI, it is essential to consider the impact of raw material in beginning and at EOL separately to consider any technological advancement over time and variation in the amount of material that goes for recycling.

It is also important to avoid counting the CO_2 emissions of the recycling process twice, in a similar way it was avoided for waste calculation in **(Eq.13)**. Hence, CO_2 emissions from both the recycling processes can be calculated using **(Eq.**19**)**.

$$\frac{\boldsymbol{R_1 \times C_{R1}}}{\boldsymbol{2}} + \frac{\boldsymbol{R_2 \times C_{R2}}}{\boldsymbol{2}} \qquad \textbf{(Eq.19)}$$

Where $\boldsymbol{R_1}$is mass of recycled content and $\boldsymbol{C_{R1}}$is CO_2 emissions of the recycling process used in stage 1 ; $\boldsymbol{R_2}$is the mass of material that have to be recycled and $\boldsymbol{C_{R2}}$ is CO_2 emission of the recycling process in Stage 7.

Stage 8 Accounts for the CO_2 emissions of the material that cannot be recycled any further; can either be incinerated or end up in landfill. Using **(Eq.20)** we can calculate the embodied CO_2 of a product in one life cycle.

$$V \times C_v + \frac{R_1 \times C_{R1}}{2} + \frac{R_2 \times C_{R2}}{2} + W \times C_L + D_p \times C_t + C_t \times D_r \times R_1 \qquad \textbf{(Eq.20)}$$

Where**,** C_v is the embodied CO_2 in extraction of virgin material, C_L is the embodied CO_2 of landfill, D_p is the transportation distance between the material and the project site and C_t is embodied CO_2 due to the transportation at Stage 3 & 6 and D_r is the distance between the project site and the recycling plant. For simplification, the distance between the project site and recycling plant is considered to be 10km.

To compare the difference between a linear use of material and circular use of material, CO_2 footprint is proposed to be calculated using **(Eq.21)**.

$$Embodied\ CO_2 = \frac{V \times C_v + \frac{R_1 \times C_{R1}}{2} + \frac{R_2 \times C_{R2}}{2} + W \times C_L + D_p \times C_t + C_t \times D_r \times R_1}{L_b} \qquad \textbf{(Eq.21)}$$

Where L_b is the expected life of the building. life expectancy of the product is less than the use life of the building, then a new product with similar or less embodied CO_2 can be used. This way of calculating embodied CO_2 would result as follows:

1. The buildings with shorter lifespan would have larger impact per year compared to buildings that are designed for longer lifespan.

2. Secondary material arriving from far distance will have higher impact due to transportation. Hence, local sourcing can be ensured.

3. Virgin material will have higher impact per year whereas, in case of reused material, the impact will be zero. Hence, reduction in the generated CO_2 can be compared.

4. If the recycling process become efficient in future, W will be reduced. Hence, reducing the overall impact.

2.7.2 What are the important key indicators for monitoring circularity in built environment?

To track progress of circular economy in the EU, indicators such as Circular Material Use rate and Recovery rate of CDW can be utilized. Circular material use rate shows the amount of recycled and re-used material in the total material demand and Recovery of construction and demolition waste accounts for material that was recovered for re-use, recycle, material recovery and backfilling operations.

The main principle of circularity is to keep the materials in flow without sending it to landfill at the EOL. To ensure circular use of material, the building components needs to be demountable. Durmisevic describes the qualitative estimate of measuring Transformation Capacity of a building using DfD aspects. Verberne uses selective DfD aspects from Durmisevic and MCI to get an aggregated score to determine the circularity of a building (BCI). From the literature in this chapter the drawbacks of BCI is clear. The benefits of using MCI to calculate embodied CO_2 if also shown in this chapter. Hence, it becomes an important indicator to assess the circularity of a building.

The MCI calculation shall also be complemented by following principles of DfD from Durmisevic-

1. Assembly and Disassembly sequence

2. Geometry of product edge

3. Connections

4. Life cycle coordination

The materials in the building that are reusable after the technical life cycle of a product must be checked with these DfD aspects to ensure disassembly and if the materials cannot be retrieved after assembling all the building components, then the MCI variables of the affected materials should be changed accordingly to assess the final circularity of the building. Hence, the above DfD aspects can be used as a checklist to ensure disassembly of the products that needs to be maintained or replaced within a use life cycle of a building and this process must not affect the components of higher life expectancy. **Figure 2.7.6** shows the assembly sequence of various building systems v/s the expected lifetime of each component. Next paragraph explains how we can combine this knowledge to analyze and treat the components of shorter life span.

In **Figure 2.7.6** a) assembly sequence is plotted on the horizontal axis at two levels. The big interval represents the assembly of various building systems whereas the smaller intervals represent the assembly sequence within different building systems. Using the knowledge of relational patterns and connection principles (section 2.3) from Durmisevic we can plot various building components on the graph. If the building reaches its use cycle within 30 years then elements below the dotted line in a) are going to reach their end-of-use before and would require repair or replacement. Even if all components reach their EOL after the use phase of the building, in both cases these components should be accessible and demountable if they can be reused to its highest potential. We can assess these components based on following simplified knowledge model-

1. Is the component connected with other components or have functional dependence on others?
    a. If yes, then are these connections fixed or flexible?
        i. If fixed, then change MCI variables accordingly of the affected components.
        ii. If flexible, then follow step 2.
    b. If no, then follow step 2.
2. What is the geometry of the project edge?
    a. If closed, then follow step 1.a.i
    b. If open-linear, then MCI variables need not be changed

Hence, this way we can use MCI and DfD aspects to inform our design and engineering decisions.

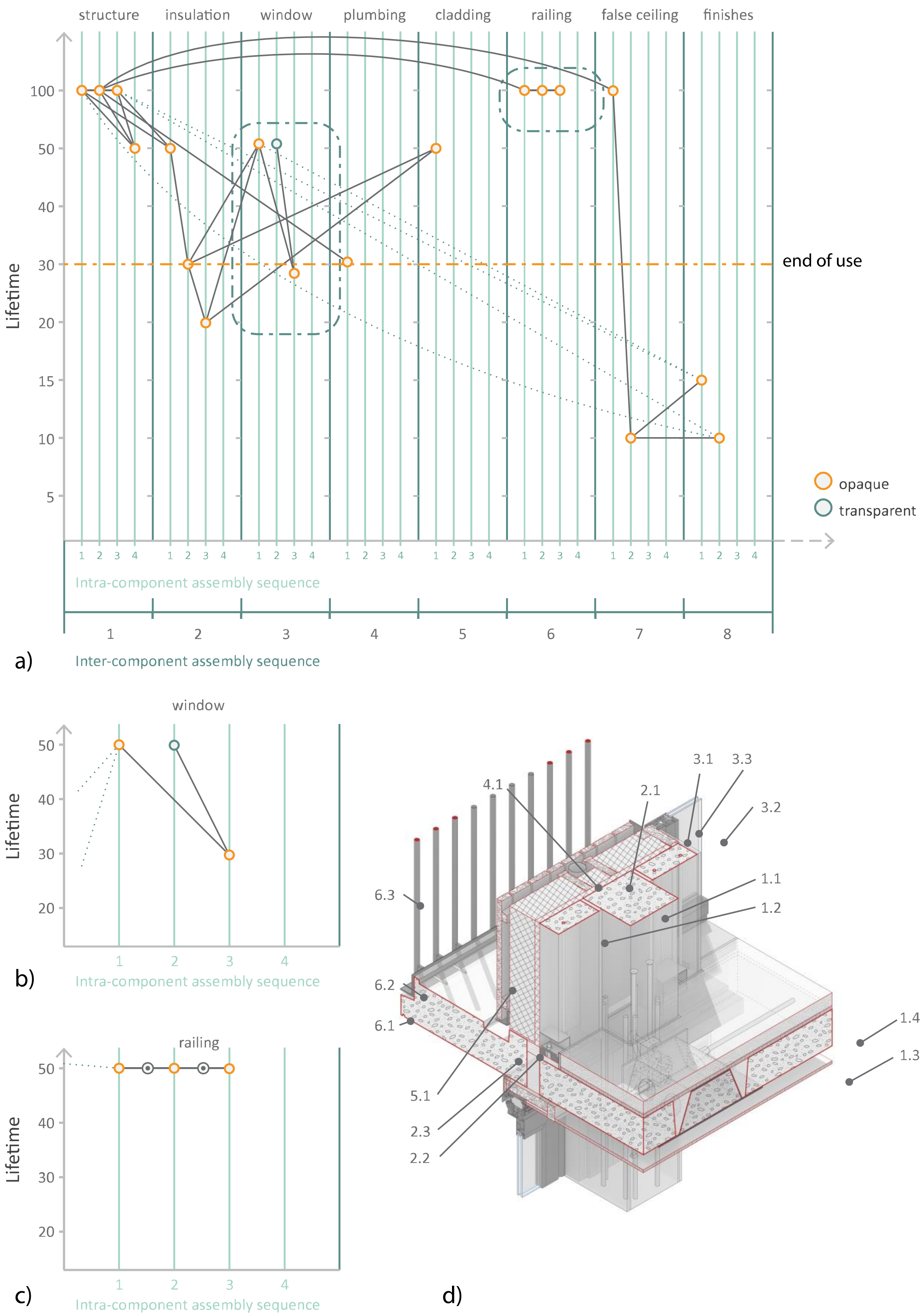


Figure 2.7.6 a) shows assembly sequence of various components within a façade junction plotted against their technical lifetime, b) shows the assembly sequence of the window c) assembly sequence of the railing and type of connections between them and d) 3D-view of the typical junction of the façade.

2.7.3 How does a building component affect the circularity of the overall building?

A building component affect the circularity of the overall building at two levels –

1. Based on the share of mass it has in the overall building, its MCI value will have more impact on the circularity of the overall building if the share of mass is high and visa-versa.

2. Its connections with other components will have impact on their MCI values. These components might have higher share of mass in the overall building (as seen in section 2.6.1).

2.7.4 How to measure circularity of a building at early design phase?

At early design phase or detailed design phase, circularity of any component can be calculated using MCI. We need to determine the variables described in section 2.6.1 and where information is not available, industry standard values can be considered. From section 2.6.1 we also know that MCI of a product can vary when it comes in contact with other building components. Hence, MCI of a product might change after the connections are decided. For products that are expected to be directly reused after the end of building use phase, it important to consider the connections carefully. Also, use of chemical joints can reduce the recyclability. Hence, calculation for circulariy can be done in two stages-

1. Preliminary Assessment - where the connections and geometry of product edge can be ignored and the overall MCI score represent the aggregated score of individual MCI

2. Advanced Assessment - where the variables of MCI changes after following the checklist of DfD aspects described in previous section 2.7.2.

Chapter 3. Circular buildings
case study

(CE100, 2016) discusses various projects that followed principle of circular economy. The challenges faced and lessons that were learnt during the execution of these projects. For example in projects -

1. **Rehafutur Engineer's House, France** - The developers found that in reusing materials, the majority of the budget goes towards labour costs rather than in the purchase of new, virgin materials. The main technical challenges lies in managing the interface between the different insulation types with the air-tightness system. Training sessions were held on the work site on air-tightness with all trades people to make this intricate system work, so collaboration was key to the success to the project.

2. **Queen Elizabeth Olympic Park, London**- Reuse of surplus gas pipeline for the compression truss structure saved 2,500 tonnes of new structural steel and enabled a cost saving of approximately £500,000. The timber decking on the bridges was screwed in rather than nailed or glued to allow for easier removal of bridge sections. Asset Disposal Contract created a form for any group to complete when requesting the free issue of assets advertised on freeusable.co.uk (which is no longer exists).

   Matching supply and demand was difficult hence, a storage space was required to dump the material until it was reused. Unfortunately, in London, space comes as a premium hence it is difficult to do the same during the development of the park. Online website wasn't enough to reach out local businesses and community to give-away the assets. But, London Legacy Development Corporation (LLDC) has their own community networks which include local businesses and arts and culture groups.

   Hub67, located in Hackney Wick was created by using 9 modular cabins that were used during the games as a temporary high street for the athletes. It also made use of the cladding material, fencing and timber removed from the park.

This chapter discusses projects that were built keeping the circular principles in mind and were located in the Netherlands to particularly follow the developments within the region and identifying the knowledge gaps.

3.1 Case 1 – Circl pavilion

Figure 3.1.1 Exterior view of Circl Pavlion, Amsterdam, Source: (Cie, 2019)

Figure 3.1.2 View looking outside from the exhibition space at Circl Pavlion, Amsterdam, Source: (Cie, 2019)

Circl pavilion is a place created by ABN AMRO bank where knowledge it gained about circularity can be shared. The building is designed on circular principles where most of the elements already had a previous life. And the raw material that was used for example, wooden structure and aluminium external façade can be put to new uses in the future. The entire pavilion spans 3350 m^2 Gross area and has 19500 m3 of volume. The construction of the building was completed in 2017 and has been nominated for BNA building of the year 2018 and Mies van der Rohe Award 2019 since then ("The making of Circl," 2018).

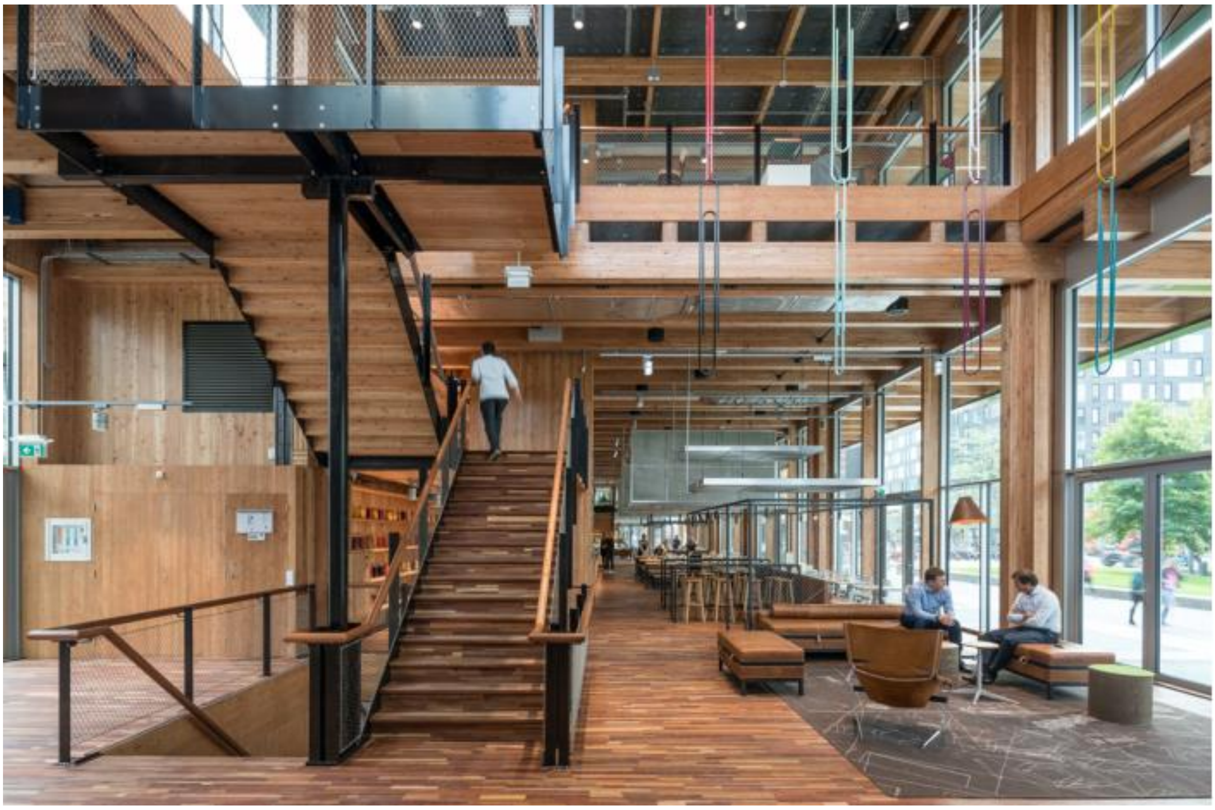


Figure 3.1.3 Ground level view towards the restaurant Circl Pavilion, Amsterdam, Source: (Cie, 2019)

Figure 3.1.4 Basement view of secondary windows Circl Pavilion, Amsterdam, Source: (Cie, 2019)

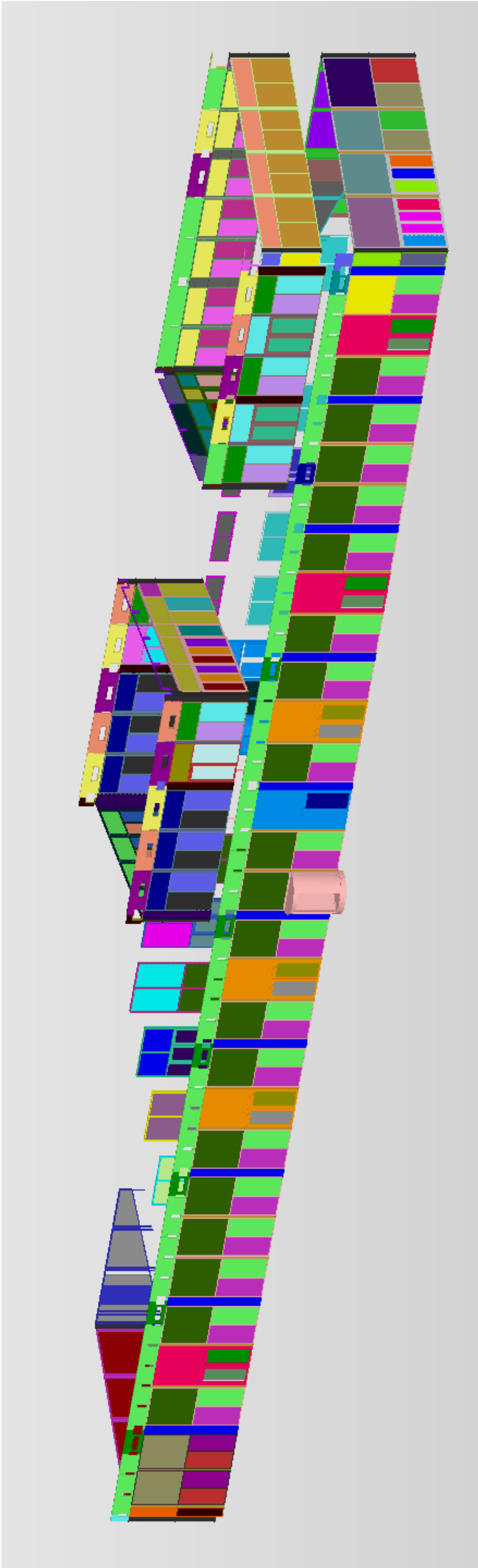
The thought behind the procurement of the building components was such that it causes least possible reduction of world resources. The building houses a 'living lab'- as a space where new innovation can be tested. For example, a portion of façade is prepared for experimenting with new materials. The TU Delft is assigned to monitor the experiments and start new ones in the 'living lab' (Cie., n.d.)

Figure 3.1.5 Arial view of the restaurant at Circl Pavilion, Amsterdam, Source: (Cie, 2019)

The life cycle of the supporting wooden structure is estimated to be 30 years which can be reused at the end of use. This required a design which makes the dismantling of the building components easy (Cie., n.d.).

"…we share what we have learned as ABN AMRO, using examples from circular pavilion in the Zuidas district of Amsterdam (Circl), We show that opportunities and business models there are for entrepreneurs in the construction industry. As doing nothing is no longer an option, we prefer a 'right to copy' rather than 'copyright'. The transition to a circular economy must be accelerated." (Circle Economy & ABN AMRO, 2017)

Through interview with Jaco Prins (Appendix 2) it was found that a material passport was prepared for all the building components and all the suppliers were requested to submit 3D models. Which was difficult as many suppliers had never prepared a BIM model for their products. This was done in order to ensure that all the building components have a digital identity and can be re-used effectively after the end of building use-phase.



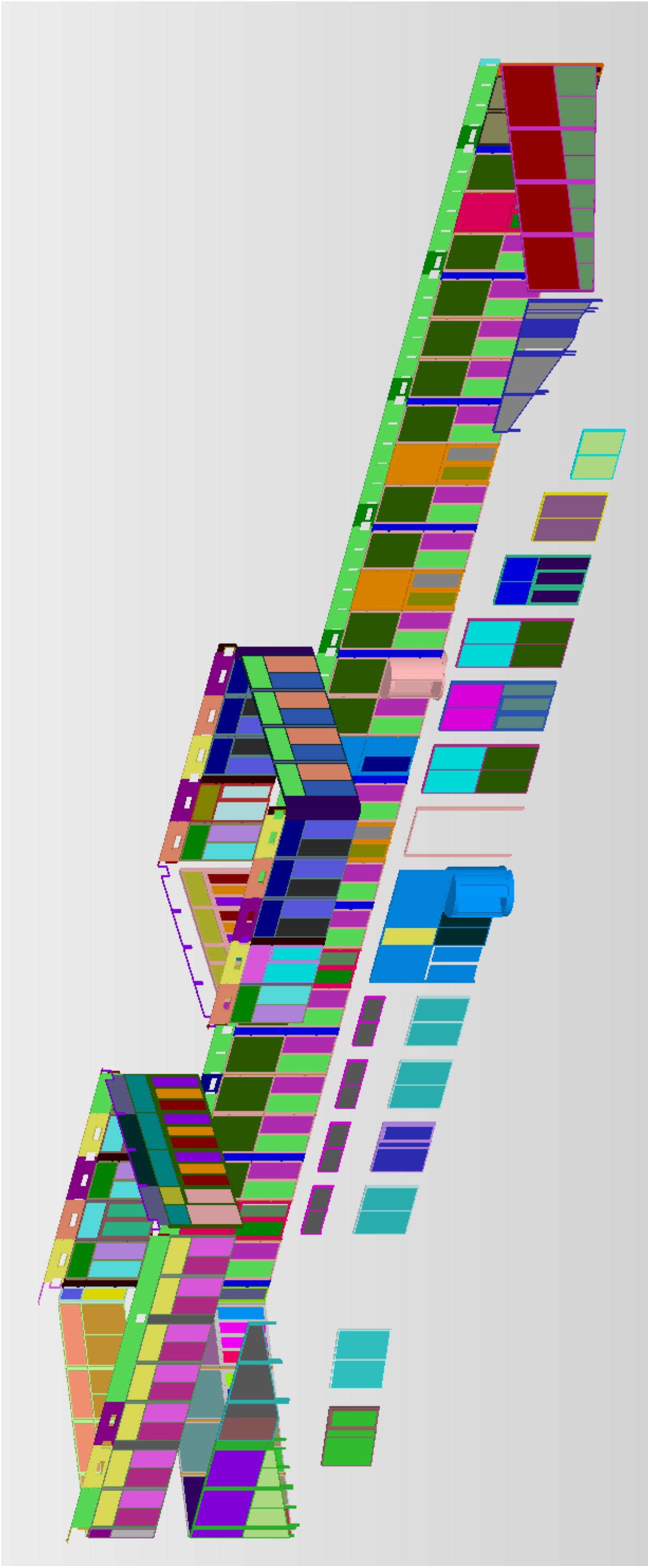


Figure 3.1.6 Different types of windows (through colour coding) assembled in the external façade of the building.

If correct labels are recorded in BIM model, a bill of material can easily be extracted. This bill of material can be used as a database for future reuse. Inferring from the building's life expectancy, all the virgin material used in the building can be returned in the economy for direct reuse.

3.2 Case 2 – Abt office Delft

Figure 3.2.1 ABT office, Delft, Netherlands, Source: (ABT bv, 2019)

ABT office was built in the period of 1999-2001 designed by Bierman Henket architects and engineered by ABT bv. The project was aimed at finding the sustainable solution by having a long life, flexibility and low energy consumption. This project received an IFD (Industrial, Flexible and Demountable) demonstration status from the Experimental Housing Foundation in 1999. A demountable and adaptable constructions system has been adopted throughout the building. The load-bearing structure is prefabricated as prefab steel concrete hat beams and 'double T' floor elements that spans 9 meter long (BiermanHenket, n.d.).

Figure 3.2.2 East facade of ABT office, Delft, Netherlands, Source: (BiermanHenket, 2019)

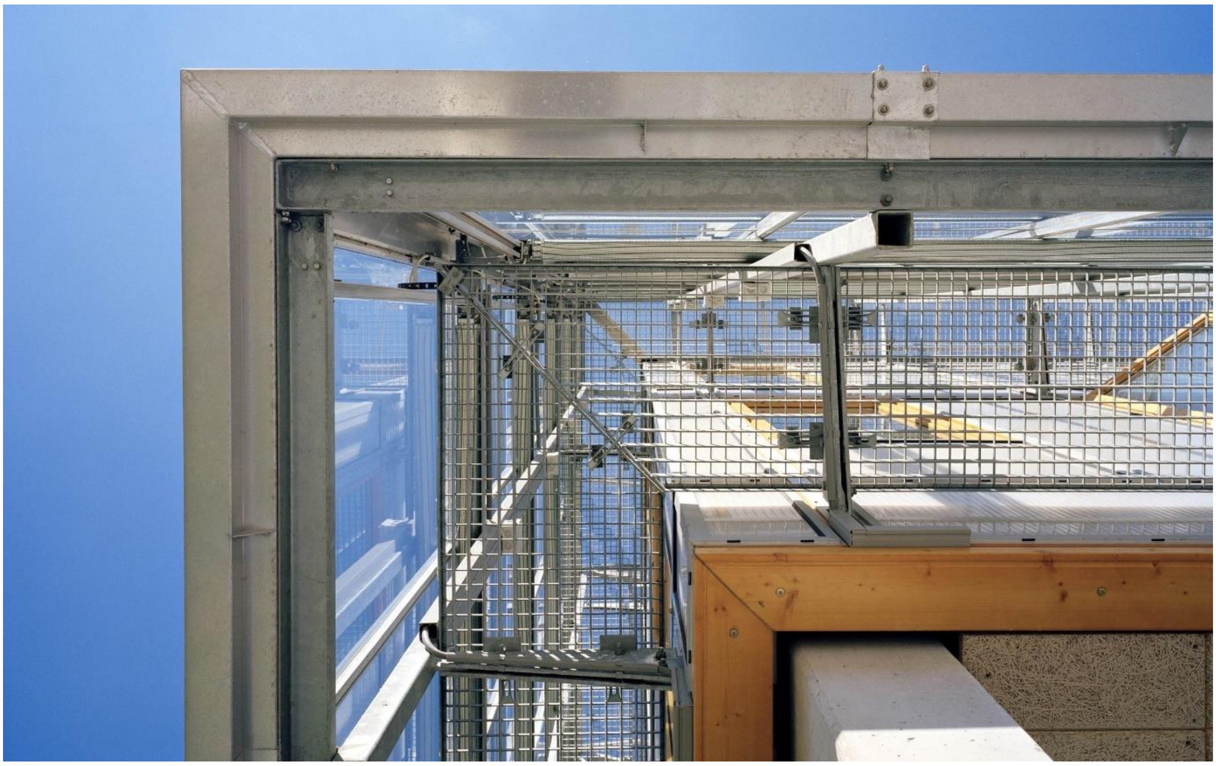


Figure 3.2.3 Facade detail of ABT office, Delft, Netherlands, Source: (BiermanHenket, 2019)

The building has a gross floor area of 2040 m² that houses about 70 employees in total from DEMO consultants and ABT bv, the two companies that are situated there. The façade of the building is designed in such a way that reduces heating loads during winters and enables natural ventilation during the summer period and is designed in such a way that the elements can be exchanged with one another(Giskes & bv, 2017).

The double-skin façade has two different materiality. The non-load-bearing external walls are prefabricated as wooden sandwich panels whereas the second skin is aluminum curtain wall system. The wooden façade can be identified as modular arrangement of standard wall, window and door assemblies. The second skin consists of an automated shading system that covers the façade during evening glare and prevents over heating during summers.

Figure 3.2.4 Interior atrium of ABT office, Delft, Netherlands, Source: (BiermanHenket, 2019)

Figure 3.2.5 Facade detail of ABT office, Delft, Netherlands, Source: (ABT bv, 2019)

As mentioned by Marcel (Appendix 2) the vision for the building is to disassemble and use its component somewhere else. This can be seen as a classical example of circular use of material. From **Figure 3.2.6** it can be seen that the second skin needs to be disassembled to disassemble the façade. The second skin also protects the main insulated wall from harsh weather conditions and possible leaks. The wooden sandwich panel is constructed to be disassembled into solid wood frame and plyboard sheet. The joinery of the three components is secured by nails. Even though this joinery is fixed in nature, it can be demounted using simple tools and re-assembled if necessary. Otherwise it is available to be used in other purpose. The walkable flooring in the second skin is supported by a structural steel angle, which is also help support the second skin. The angled steel section is connected with the main structure with help of another steel plate. This increases the transformation capacity of the façade without minimum demolition.

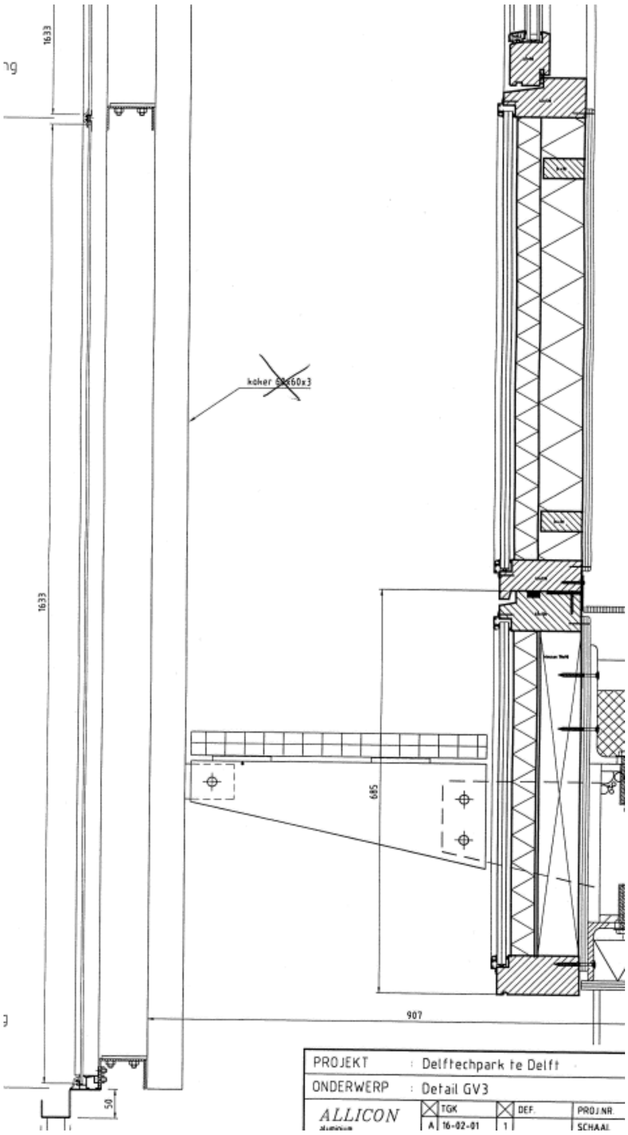


Figure 3.2.6 Wall section through the double-skin facade, Source: ABT bv, 2019

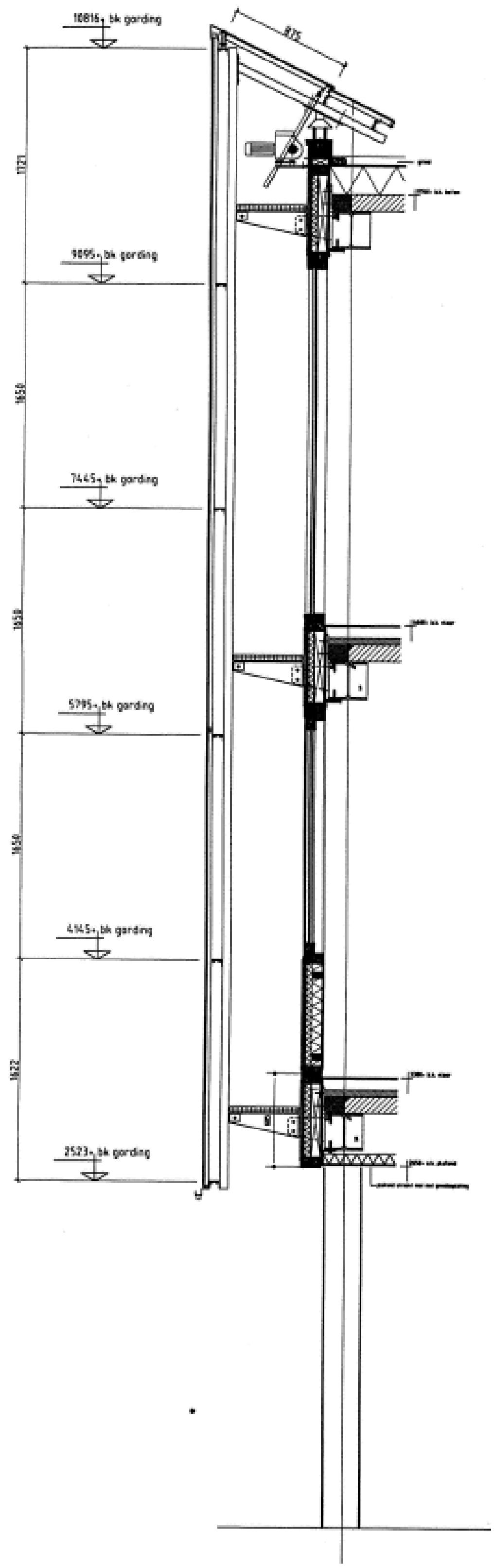


Figure 3.2.7 Complete vertical section of double-skin façade, Source: (ABT bv, 2019)

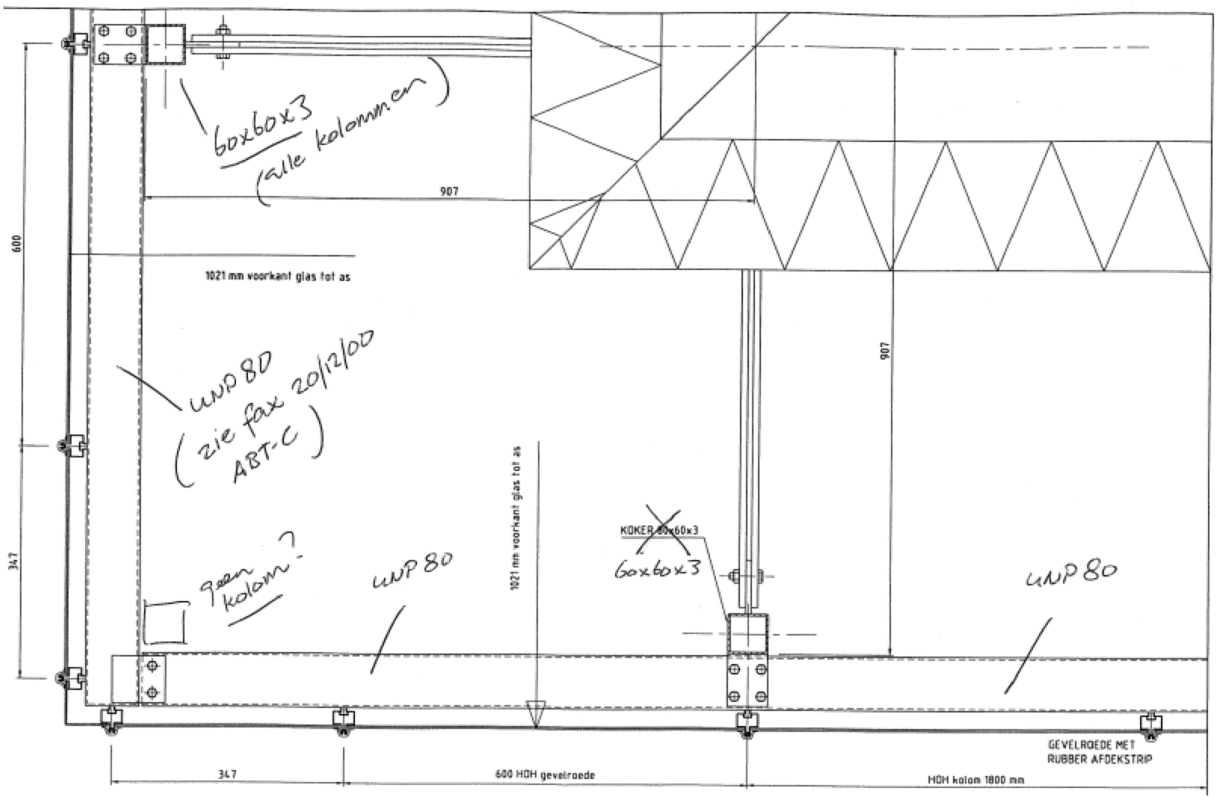


Figure 3.2.8 Plan view of the double-skin facade system, Source: (ABT bv, 2019)

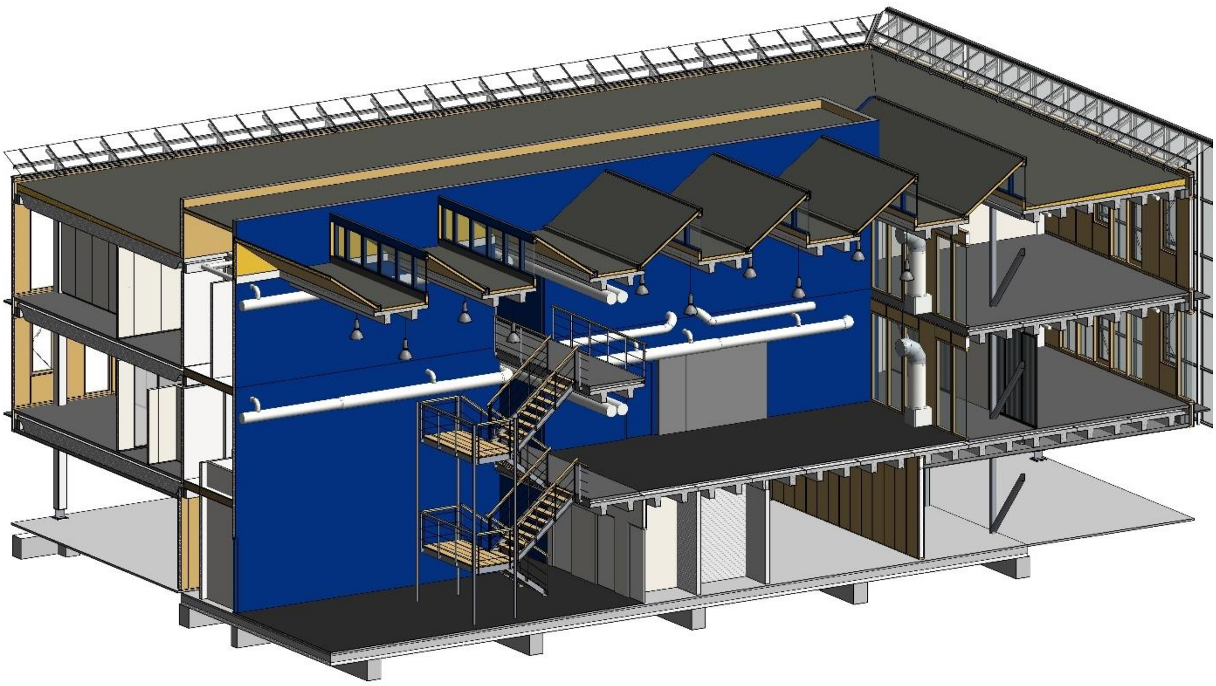


Figure 3.2.9 Sectional rendering of ABT office, Delft, Netherlands, Source: (ABT bv, 2019)

3.3 Case 3 – Brummen Townhall

Figure 3.3.1 Brummen Townhall, Netherlands, Source: (RAU BV, 2018)

Brummen Townhall is located in Brummen, Netherlands and constructed in the period 201-2013. This project was commissioned by the municipality to build a workspace with 20 year service life because of the frequently shifting municipality borders. For this brief, the design was made for disassembly and materials were re-usable and renewable. Almost 90% of the material that were used in the project can be re-used. The suppliers and manufacturers were involved at early stage of design which ensured maximum component, material and product value while disassembly. A material passport was also generated which gave identity to raw materials and details were known including use in second life (CE100, 2016).

Figure 3.3.2 Brummen Townhall, Netherlands, Source: (RAU BV, 2018)

It is the first building that was realised with building as a resource depot due to the collaboration between the municipality, BAM, RAU and Turntoo. The existing Monumental Villa from 1980s was restored and the new construction enhances it (RAU BV, 2018). The materials used in this building will return in the economy by 2033. Hence, will not reflect in CMU before 2033 as compared to earlier example where the building was designed using virgin material in 2001 and is now available to be disassembled and serve another purpose.

Figure 3.3.3 Brummen Townhall, Netherlands, Source: (RAU BV, 2018)

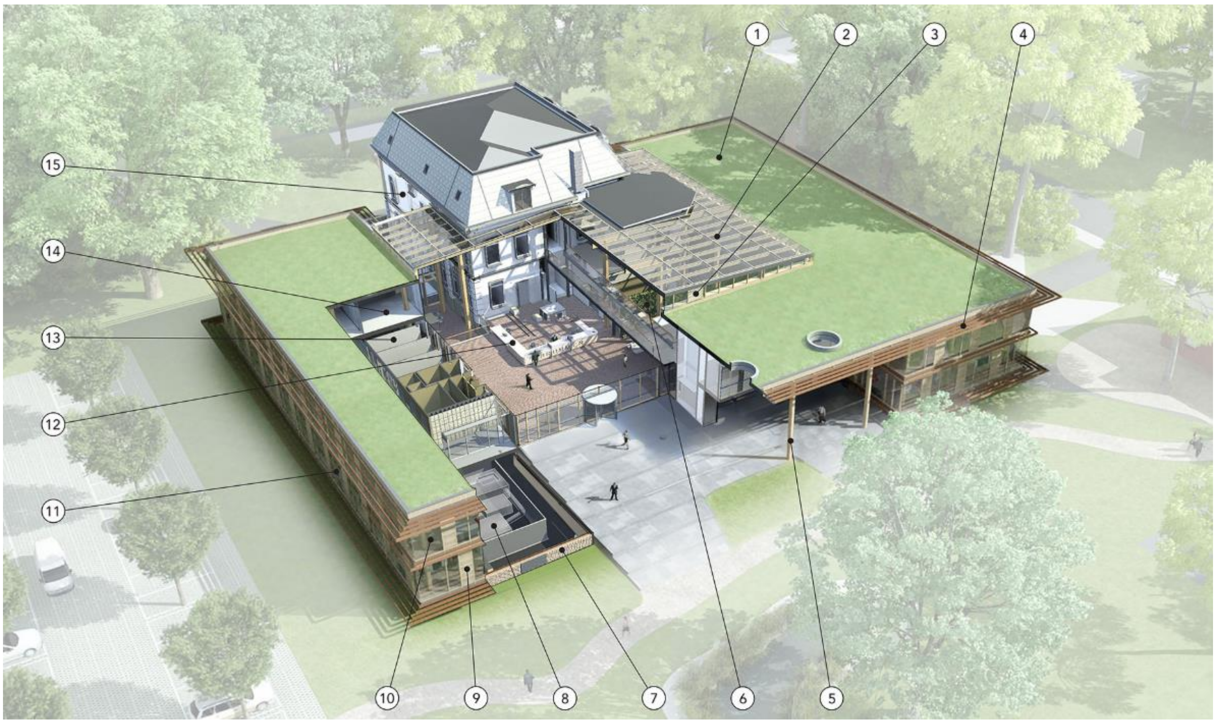


Figure 3.3.4 Sectional view of Brummen Townhall, Netherlands, Source: (RAU BV, 2018)

The modular design enables disassembly as well as reduces the construction time, whereas the foundation is part of the historic structure which will remain unchanged after the new construction is dismantled after 20 years of use phase. It was a challenge to convince the client that obtaining the material passport and all the necessary data from the suppliers is important because of the new concept of Circular economy.

3.4 Case 4 – Emergis project

Rijkswaterstaat Terneuzen was the most sustainable commercial building in the Netherlands by 2011. And received 4 stars in the GPR score and scored of more than 8 in all five categories of assessment ("GPR Projects - Rijkswaterstaat Terneuzen," n.d.). In mid-October 2018 the building was demolished by New Horizon such that quarter more than expected material can be used (van der Werf, 2017a) in the expansion of mental health institution- Emergis' children's and youth clinic Ithaka in Kloetinge. Luning designed the timber construction of the expansion project based on available beam dimensions ("Emergis builds circularly," 2018).

Figure 3.4.1 The disctrict office of Rijkswaterstaat in Terneuzen, Source: (van der Werf, 2017b)

The design process was carried out by analyzing the specification and construction documents that were submitted with the Rijkswaterstaat building in 2000. A bill of material was prepared after documenting all the usable materials and various structural options were explored digitally as shown in **Figure 3.4.2**. This availability of information helped structural engineers to visualize options for design of the new structure. In this case, the material was trimmed and extended to fit the design at some cases. Whereas, maximum amount of material was directly reused.

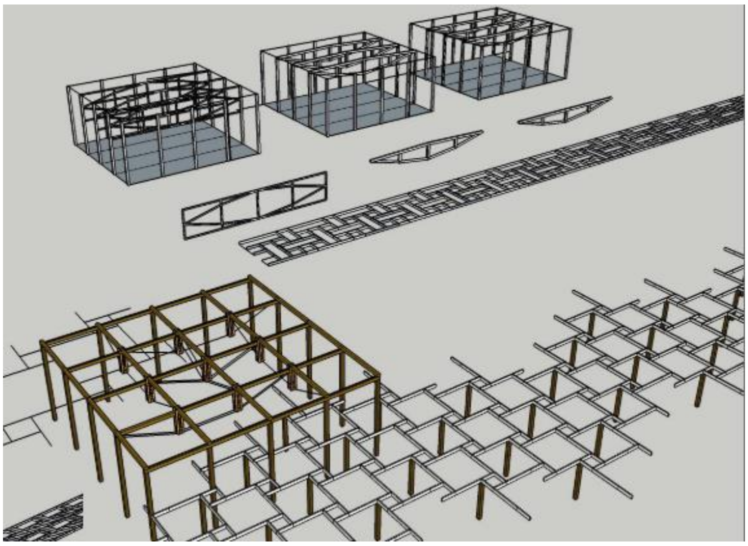


Figure 3.4.2 Design exploration of Timber structure for Emergis-Ihtaka, Source:(B.v., n.d.)

Figure 3.4.3 Construction of the Emergis-Ihtaka using the timber structure from Rijkswaterstaat in Terneuzen, Source: (B.v., n.d.)

Figure 3.4.3 shows the final design and erected timber structure on site. In **Figure 3.4.4** we can see the complete timber construction that was used from Rijswaterstaat, Terneuzen.

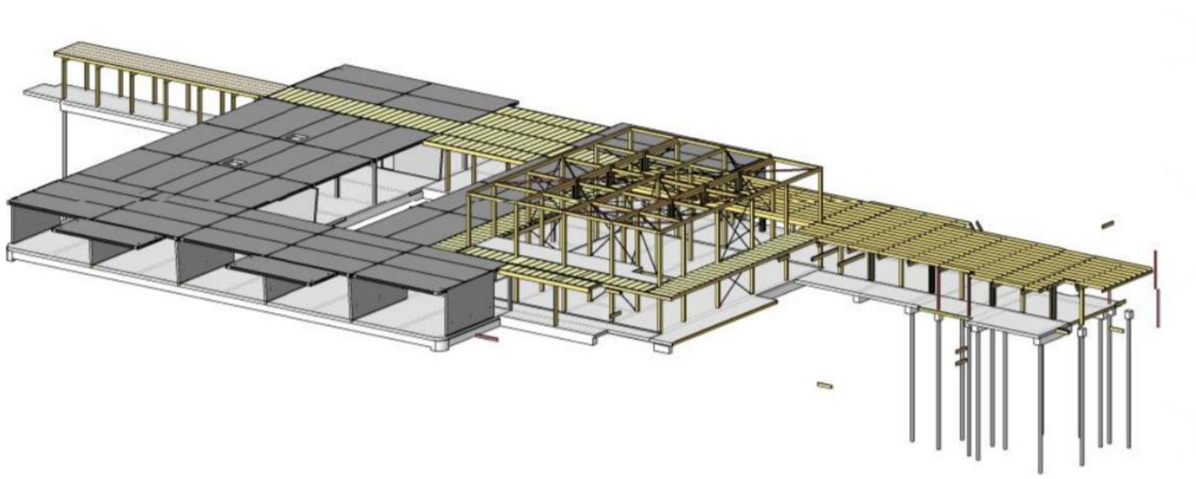


Figure 3.4.4 Emergis project by ABT and LUNING, Source: (B.v., n.d.)

Figure 3.4.5 shows the detail of the timber construction with joinery holes from the previous structural system.

Figure 3.4.5 Timber structure detail of Emergis-Ihtaka, Source: (B.v., n.d.)

3.5 Expert interviews in the procurement, design and construction process

Through the expert interviews mentioned in Appendix 2 it can be concluded that procurement plays an important role if secondary material is used in designing buildings. There is no transparency of information that exist between the owners of the material and the designers on a large scale. The use of secondary material depends on case by case. If the information is not available, virgin material is sourced instead and said to be reusable at EOL. This method is also supported by MCI and other circularity indicators. By assuming a extended lifetime of a material at the beginning of the design yields high circularity value. Goals of becoming a circular economy is disconnected with the environmental gains associated with it. Environmental data is available only for new materials. There is a lack of database that considers environmental impacts of refurbished products. To assess this, LCA methodology can be used.

There are two major takeaways from the interviews conducted-

1. There is no clear methodology to assess the benefit of using secondary material.
2. There is need to collaborate with architects, engineers and contractors to make sound decisions for using secondary elements.

3.6 Conclusion

This chapter identified the knowledge gap existing between designers, engineers and contractors with regards to using secondary material. This forms the brief for the assessment framework proposed in Chapter 5.

All the buildings studied in this chapter are so called circular because most of material is either reused or directly reusable at end of building's use phase. The virgin structural and façade components used in Circl pavilion will return to the system by 2047. This means that the reusable mass will reflect in CMU indicator after 2047, if reused. This does not align with the EU goals to become a circular economy if the material used currently in new projects is virgin. Similarly, Brummen Townhall finished its construction in 2013 with virgin material mostly. This mass of material will return back in the system by 2033 and will not reflect the progress towards becoming a circular economy until then. But, ABT office, finished its construction in 2001 and was designed to last 20 years. All the materials used in this building are now available to be returned in the system. Similarly, Emergis project already used structural components from an existing building, this would reflect in the CMU indicator immediately.

It can be concluded that, the time to use virgin material has come to an end if Netherlands wants to become a circular economy by 2050.

3.6.1 What key parameters are needed in making a decision to utilize secondary material at early design stage?

There are two parallel requirements that go hand -in-hand in order to procure secondary material –

1. Design requirements
2. Environmental benefits

Design requirement are majorly revolved around the sizes, materiality, quantity and thermal/acoustic performance. From the study of Circl in Section 3.1 and expert interviews in Appendix 2, it is known that all building elements must have a digital identity stored in one place enabling transparency regarding its-

1. Life expectancy,
2. Length, Depth and Height,
3. Materiality
4. Technical performance – U value, Thermal conductivity and Acoustic velocity
5. Quantity

From section 2.3 we understand that life expectancy of a product is a must to be known in order to determine assembly sequence, geometry of edge and connections between different components. Circularity goals on the other hand intends to lower the environmental impact and hence, information regarding following factors is required-

6. Volume & Density
7. Fraction of recycled content (if the material is new)

8. Fraction of re-used content (if using secondary material)
9. Fraction of re-usable content (If the product life is still left)
10. Fraction of recyclable content (If the product is demolished)
11. Efficiency of the recycling processes
12. Life expectancy

From section 2.6.4 we know that to measure the environmental benefits an estimation of embodied CO_2 is required. For new materials it is essential to know the virgin content, recycled content and transport needed to bring it to the site. This data can be retrieved from the ICE database (Circular Ecology, 2019) or Nationale Milieudatabase (Milieudatabase, n.d.). And it is known that the values of virgin and recycled content is necessary to determine the embodied CO_2. Hence, Location of the project should be known.

From the study in section 3.1-3.4, contradictory arguments were seen regarding cost as a driving factor to reuse secondary material. (Guldager Jensen & Sommer, 2018) mentioned that design and construction costs will most likely be less significant than the total cost of ownership for a leased building. The clients are requesting buildings and structures with optimized cost of ownership. In a project of 3XN and Danish contractor MT Hojgaard, the transformable super structure resulted in a profit of DKK 35 million which turned out to be 4% of the total cost of the building that was DKK 860 million. The cost of operation and operation of a building like 'De Fire Styrelser', over 30-year period results are approximately 50% of the value of the contract with the client. This forces the contractors to focus on the Life cycle Costs (LCC) of the project and not on the construction costs. The cost for transportation of heavy precast concrete is relatively higher than timber or steel hence, circular potential for concrete must be regional. Also, the cost of landfill are expected to rise more than average price levels. The embodied CO_2 emissions are majorly related to the structural components. Reusing structural components two times saves up to 45% of the total CO_2 emissions caused by the super structure. Even though literature suggests that in current 'business as usual' the material and construction costs are marginal compared to total ownership cost, it is idealistic to measure the costs in expectation of rising landfill costs.

3.6.2 What are the challenges of circular procurement and construction?

The main challenges seen in circular procurement is the transparency of information. This is due the following factors-

1. Lack of information about the available material.
2. Lack of transparent information about environmental benefits.
3. There is no standardized guidelines for Design for Disassembly.
4. Existing online marketplace does not have less or no information about materiality, mass, geometry and life expectancy of building products.
5. Lack of aggregated assessment criteria to measure circularity, environmental impacts and economic drivers like cost, preliminarily.

Chapter 4. Material databases – overview

This chapter discusses platforms that intend to create standards for creating material passports of existing as well as new real estate in the first two sections. In section 3, 4 and 5, online marketplaces that sells secondary material will be discussed. Madaster and BAMB will be rated based on what was learnt in the previous chapters.

4.1 MADASTER

The aim of making a material passport for building components is to harvest these materials at demolition stage. This would avoid burning or dumping of these materials. The material can then be recycled and retain its value and life span for further use. MADASTER's goal is to keep the material in use as long as possible. Hence, preventing burning, dumping and delaying recycling (Zijlstra, 2017).

> *"The MADASTER materials passport is set to become the new standard in the real estate sector. Generating a digital materials passport for every building opens up the possibility of creating a circular economy within the construction industry."*(Madaster, 2019)

The passport created through MADASTER has to be initiated by the clients (owners of the building) to be used by architects and contractors for new-build or renovation projects. The passport can be initiated by clients and used by architects and contractors in new-build and renovation projects. In this way it becomes an independent public platform for private individuals. (Madaster, 2019)

Thomas Rau states MADASTER is like a 'land registry' for materials. By giving a digital identity to materials they can no longer disappear as waste. MADASTER also acts as an online library of materials in the built environment. In their platform you can access the information of materials that are used in a building with their quantities and location. This way the building becomes a pool of material with their circular value. At early design stage MADASTER Circularity Indicator (**Figure 4.1.3**) provides the degree of circularity of the new project property. The construction process can be documented, saved and viewed by the parties involved and the final building file can be delivered to the client. This makes the administration of the building easier in future.

MADASTER's solutions partner W/E Consultants performs environmental performance calculations for buildings that are registered in MADASTER. The MPG (MillieuPrestatie Gebouwen) score and report appears on the platform when requested. For clients it becomes easier to gain insight about the performance of their real estate.

To get started with creating a material passport with MADASTER, the BIM model needs to be created as per the list of requirements stated by them. BIM model is central to the Madaster platform and input of the building data has to be done using an IFC format. The key important necessary requirements are –

1. All the elements must be assigned with materials, this will be used to categories the types of material and the percentage of their quantity relative to total weight.

2. To classify various materials for example, door, window, skylight etc. a 4 digit NL/Sfb has to be used. It is a Dutch classification of building elements.

3. Material quantities are exported by Volume (m^3)

The platform has 4 key information about the material. First, the materials are categorized based on which building layer they belong to. This is ensured by the classification of all the elements according to NL/Sfb and assigning the correct material in the BIM model. This information is displayed illustrated effectively as shown in **Figure 4.4.1**.

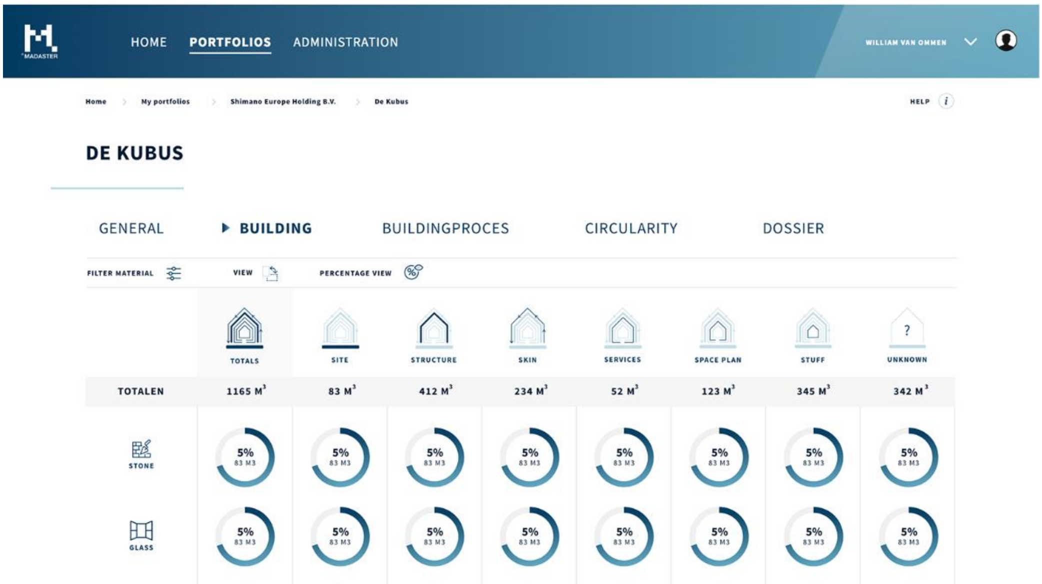


Figure 4.1.1 Building materials categorised based on which building layer they belong to, Source: (Madaster, 2019)

Second, volume of material present in different 'phases' of the building process can be tracked. For example in **Figure 4.1.2**, there are 5 stages of the building process and each process demonstrates how much volume of material was present.

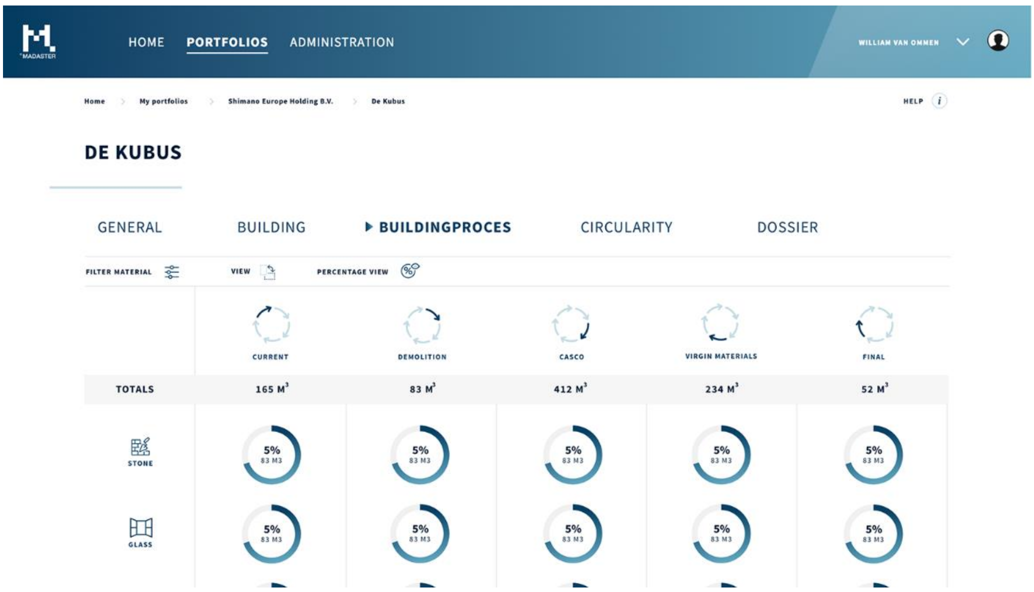


Figure 4.1.2 Tracking of material volumes in different phases of the project, Source: (Madaster, 2019)

Third key information is about the circularity value called as CI (Circularity Indicator) value for different layers of the building as well as the total score. The platform also shows how much virgin material is used during the building process. This is illustrated as a concept interface in **Figure 4.1.3**.

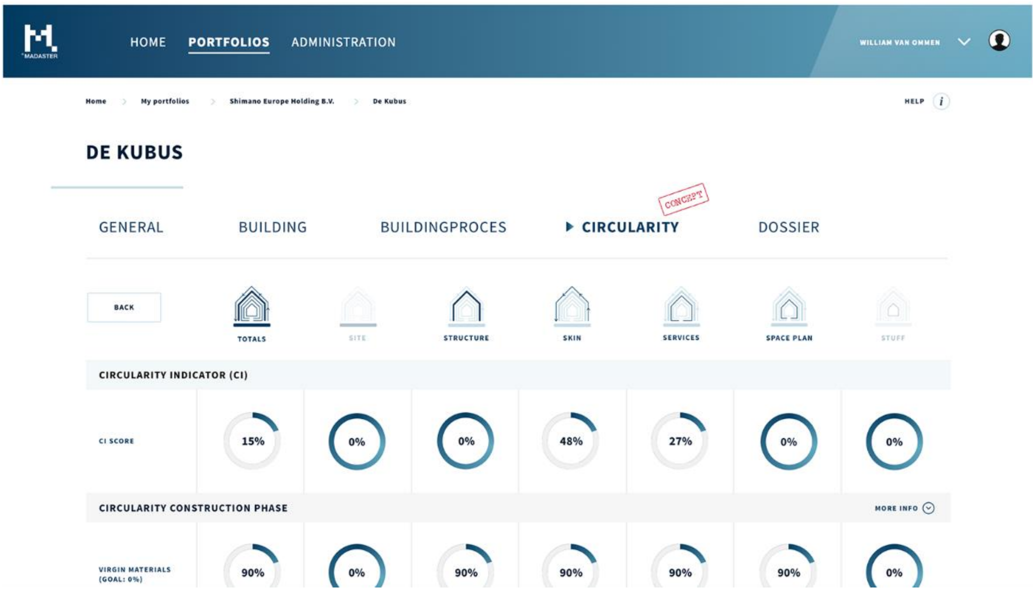


Figure 4.1.3 Circularity indicator for different components at different stages. Source: (MADASTER, 2019)

Fourth, Net Present Value (NPV) of various materials is displayed collectively as shown in **Figure 4.1.4**.

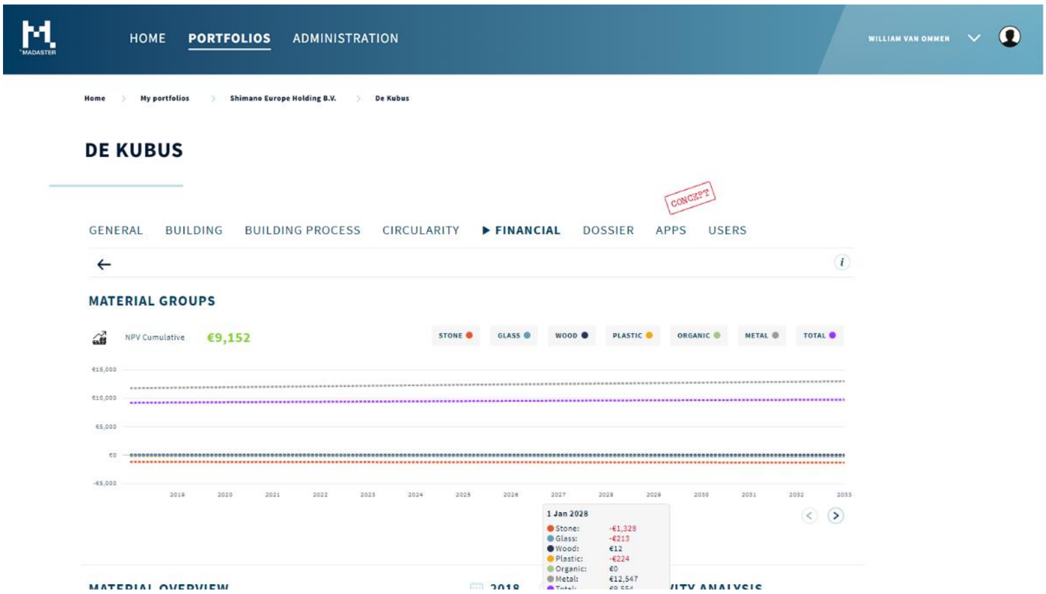


Figure 4.1.4 Net Present Value (NPV) of various material displayed collectively in Madaster platform, Source: (Madaster, 2019)

In addition, for prospective re-sale, the platform provides various IFC files to explore potential reuse in new-build of renovation project by architects or by contractors. See **Figure 4.1.5**.

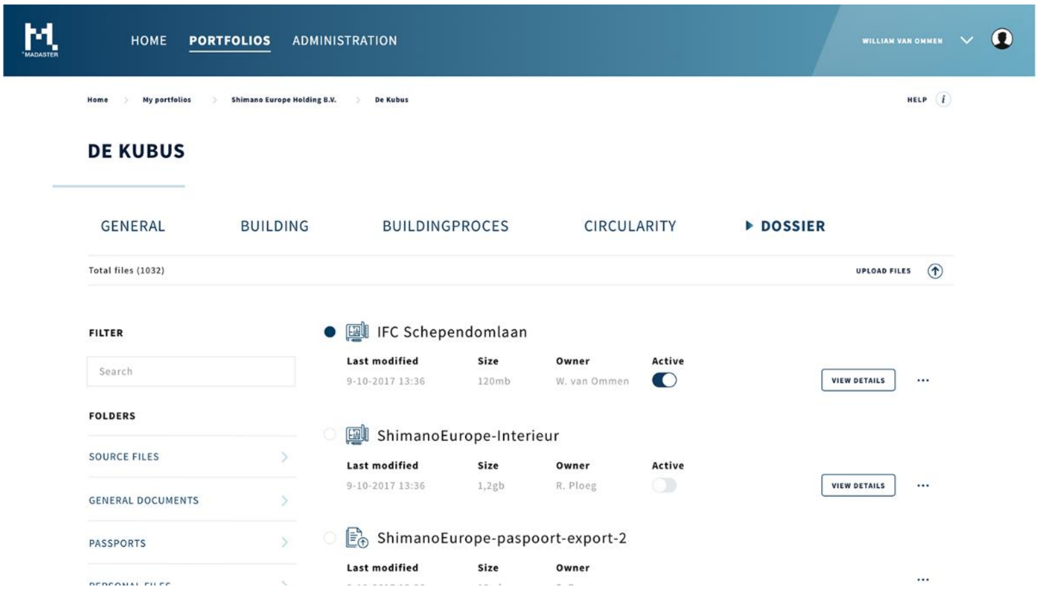


Figure 4.1.5 IFC file of a part of the building, Source: (MADASTER, 2019)

4.2 Building As Material Banks (BAMB)

BAMB's mission is to facilitate the shift to circular building sector. They acknowledge the potential of effective recovery and reuse of components. With this, easy access to this information is crucial to ensure re-use. Hence, they have created a web-based material passport platform as a one stop shop for materials with an identity and circular economy value. It is a joint project with 16 partners from across 8 European countries investigating and creating solutions. It started in September 2015 as an innovation action within the EU funded Horizon 2020 program (Cornet et al., 2016).

They have developed Circular Building Assessment (CBA) Prototype which is in technical development phase to create a user friendly and pragmatic tool. **Figure 4.2.1** shows the flow of information to perform a CBA. It can quantify and compare design approaches, based on regular versus circular scenarios for instance reusing, design for future reuse while highlighting environmental and economic benefits.

They intend to guide designers including architects, engineering firms as well as urban planner and also other stakeholders such as property developers and building owners. Hence, three tools are under development within the BAMB project.

1. **Reuse potential tool** – determines technical reversibility of the building design to promote high quality reuse.

2. **Transformation capacity tool** – intends to assess the spatial reversibility of the buildings design to increase the possibility of future transformation.

3. **Reversible Building Design Protocol** – This is a combination the tools above which is intended to help assess the technical and spatial reversibility of the building at early design phase.

All the three tools above are qualitative way of estimating circularity of building design. In Chapter 2 it has been concluded that quantitative estimate of how much material that goes into a building is reused or recycled is needed.

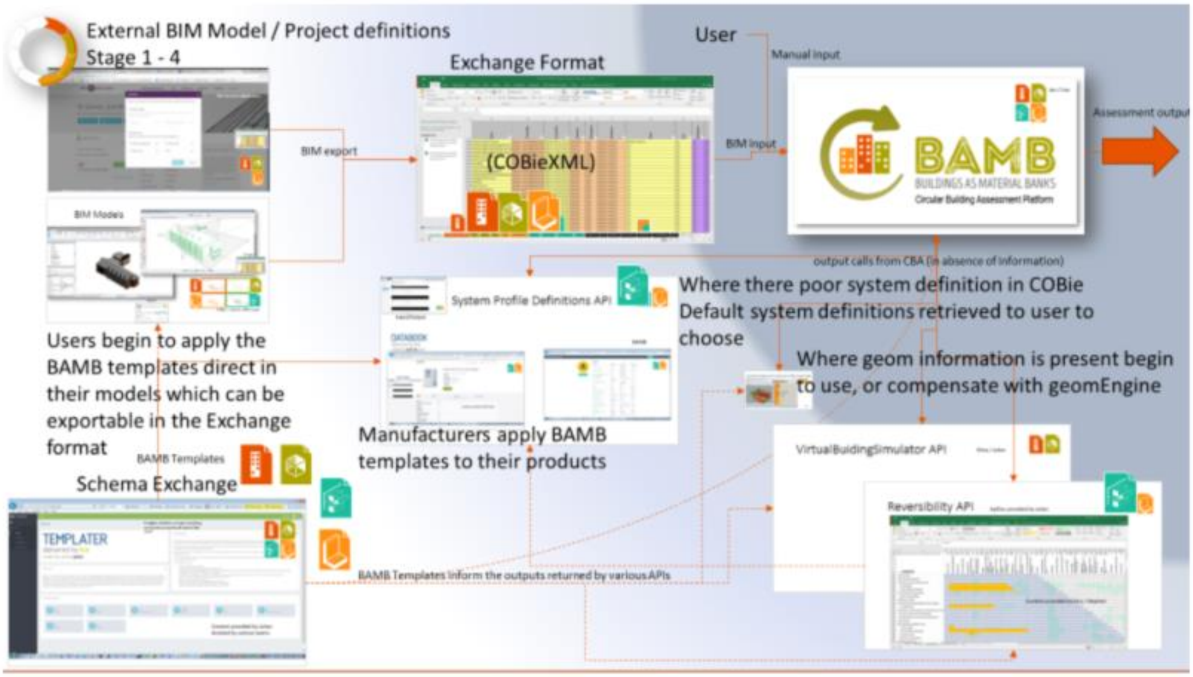


Figure 4.2.1 Circular Building Assessment prototype by BAMB, Source: (BAMB2020, 2019)

In summary Madaster and BAMB are platforms that intend to analyse the circularity of the existing real estate as well new designs. To accelerate the use of secondary material

4.3 OPALIS

Opalis is an online hub of suppliers that provide second hand building components ranging from stone paving, wood & steel structural components, bricks, insulation, wooden paneling, window frames, doors, stairs, flooring, partition walls and false ceiling. It is a strong network of suppliers based majorly in Belgium. But, few companies including Duurzaam Solutions, Van Baal Materiaalhandel, Gebruiktebouwmaterialen.com and Belle Epoque house are located in the Netherlands.

The website supplies information regarding the available products, treatments required before use, cost and facilitated by an image of the stock in most of the cases. The products are categorised by the function of their previous life such as, partition walls, window, doors etc. These categories then lead to various dealers who can provide that material. The website does not conduct sale online but is an aggregated list of suppliers based on what product you need. Same supplier can be seen in various categories depending on the variety of material they have. Detailed information regarding the sizes, quality, quantity and aesthetics varies from supplier to supplier as there is a lack of a standard list of labels. is accessible by visiting the warehouse. To get an overview of available stock, dealers have provided a gallery of images of material lying at their warehouse(s) as shown in **Figure 4.3.1**. Detailed product data would benefit the design and engineering teams to consider products in designing of new buildings or renovation projects (Cornet et al., 2016).

Figure 4.3.1 Warehouse image of Van Baal Materiaalhandel, Source: (Opalis, n.d.)

4.4 Harvest Map

Harvest map is a marketplace for professional upcyclers, plotted on a map of Netherlands as shown in **Figure 4.4.1**. It provides information related to date of upload, quantity and size facilitated by an image of the product. The product ranges from structural components, insulation, used greenhouses, raw wood, windows and anything that can be used in building services.

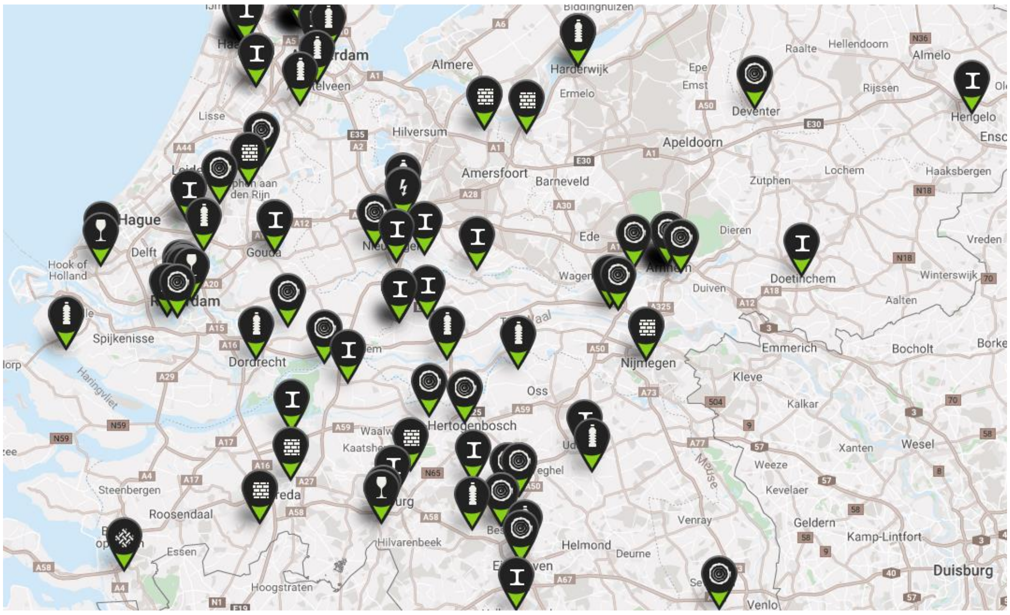


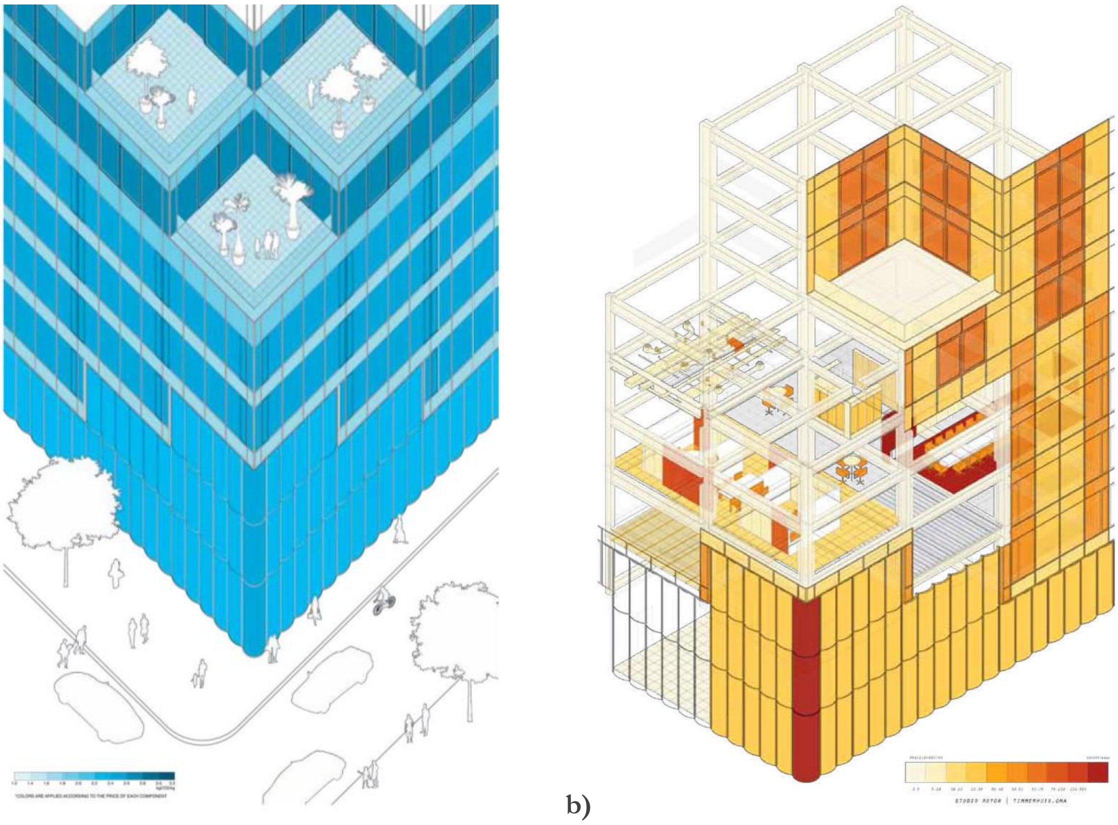
Figure 4.4.1 Location of products by material across the Netherlands. Source: https://www.oogstkaart.nl/

4.5 New Horizon

Aim of New Horizon is to collect useful raw materials from buildings which can either be directly re-used or good enough to make a new product. Through New Horizon urban mining, raw materials are assigned new use before dismantling. This is then coordinated with the timeline of the new project. Upstore stores material from New Horizon and enables the sale of circular products. The goods are supplied by the citizens and are made available to purchase online as well as in physical environment (NewHorizon, 2019).

4.6 ROTOR Deconstruction

Studio Rotor is a design practice that investigates the of material environment. Rotor Deconstruction is separate entity launched in 2016 to promote the reuse of building components through practice, case studies, exhibition and publication (Rotor, n.d.). 'Deconstruction' by van den Heuvel & Sanz, (2017) analyses various case studies by innovative assessment visuals such as in **Figure 4.6.1**, it shows the Embodied CO_2 of elements in façade of Timmerhuis, Rotterdam in a 3-dimension model of the building.



a) b)

Figure 4.6.1 Embodied CO_2 of building elements in the facade of the Timmerhuis in Rotterdam, OMA. Made by Duong Vu Hong, Benjamin Summers, Katarzyna Sołtysiak, Melanie Kwaks. Source: (van den Heuvel & Sanz, 2017)

Many exercises related to re-use are described in van den Heuvel & Sanz, (2017). For example, student of Studio Rotor explored the re-use potential of dismantled steel structural components from Youth Hostel, Ockenburgh (2010) in an academic design exercise.

Criteria	MADASTER	BAMB
Circularity Indicator	Low Developed by alba concepts, it is a qualitative estimate of circularity of a building. Does not inform how much amount of material is reusable.	Low Assessment of circularity is purely qualitative and does not inform the quantity of material reusable or recyclable.
Technical parameters	Medium Labels are dependent on IFC template.	Medium Labels are dependent on IFC template.
Geometrical information	Medium Material passport is created for each project.	Medium Material passport is created for each project.
Transparency of information	Low There is no centralised place for secondary material that is available to be reused.	Low There is no centralised place for secondary material that is available to be reused.
Environmental assessment	Unknown No information was found to support this comparison.	Unknown No information was found to support this comparison.
Ease of use	Unknown This was analysed based on the information that was available on the website freely. The assessment requires a BIM model with IFCs, which not usually available at early design phase.	Unknown The Circular Building Assessment tool is still under development. From the information available online, it seems to be compatible without having to use IFC. Custom templates are being prepared to set default values for standard materials.
Secondary material	Unknown There was no information found on assessing secondary materials which were not part of an existing building.	Unknown There was no information found on assessing secondary materials which were not part of an existing building.

Table 4.6.1 Summary of two state-of-the-art tools with the respect to the requirements from previous literature review

4.7 Conclusion

This chapter fills the knowledge gap between designers and owners of material banks. A list of essential parameters is prepared and how this material shall be integrated with the design process is answered.

4.7.1 What parameters should be implemented in material databases to accelerate use of secondary materials?

In current practice it is seen that documentation of secondary materials in not defined in a standardized manner. Designer analyses a building with different set of glasses as compared to engineering approach. From expert interviews (Appendix 2) it is known that designers want to have knowledge regarding the size, geometry, aesthetics, quantity of the material in order to visualize it in the design process. Whereas from circularity goals the materials we use need to be in circular flow even after one use cycle. Hence, material banks need to take into account the need of designers and circularity goals in order to escalate the use of secondary material.

In Section 4.1 & 4.2 it is seen that practices like BAMB and MADASTER are making an effort to standardize this documentation process via incorporating different labels like, material, life, sizes within a BIM model. BAMB also mentions that users should be required to input minimum information and where the data is not available, they intend to develop parallel web services to automatically populate data (BAMB2020, 2019). This would maintain uniformity in the format of information throughout the real estate sector as both the methods follow ISO 16739:2018 (Industry Foundation Classes). They also use their own Circularity Indicators to make a comparison and differentiate from other stakeholders. Section 0 & 2.5.1 elaborated on qualitative and quantitative approach to get an aggregative score for Transformation Capacity and Building Circularity Index as a management tool.

From the study DfD aspects (Section 2.3) it is important to know the type of connections between different functional groups as well within a functional group in order to assess transformation of various material at End of Life (EOL). Relational patterns (Durmisevic, 2016) or Graph theories (Denis et al., 2017a) help assess the transformation potential digitally and make better decisions regarding products with lower lifespan than the use life cycle of a building.

The objective of the research is to accelerate the use of secondary material at early design stage and this can be differentiated from the objective of stakeholders like BAMB and MADASTER which enables decision making for circular design. Hence, this research focuses on designer's requirements to design innovatively while being aware of impact of circular design on environment. As per a designer's concern, material banks should become transparent and actively engage with the design process. A marketplace of secondary material (such as Harvest Map & Opalis) must also incorporate the parameters like-

1. Life expectancy,
2. Location,
3. Volume,
4. Dimensions – Length, Depth & Height
5. Material,
6. Thermal performance,
7. 3D geometry,
8. Product codes (such as NL/Sfb)
9. Reused, Recycled content (for MCI)
10. Relationships with respect to type of connections within a component

4.7.2 How the use of secondary material be accelerated? How to integrate material database in the design process?

To accelerate the use of secondary material bank, it must be actively engaged with the designers and engineers. In Section 3.4 it was seen how dismantled wooden structure was used by engineers to propose a second use in a different building. This was enabled by a bill of materials facilitated by quantity and sizes of all the elements. This enabled the constraints of the available material in the beginning itself.

In case of huge amount of available material, going through a bill of material is not considered a viable option in this research. Hence, a material explorer is prepared which would convert a tabular database of material into a visual interface. This interface can enable quick overview of the available material and filtering based on design requirements.

One way to do this is manual searching the online databases such as Opalis, Harvest map, Excess Material Exchange (EME) or visiting various warehouses and shopping for materials. Or the design team gets the information/ samples/ demos of refurbished building products with respect to transparency in available supply, specifications and certifications.

(Denis, 2017) elaborates on the state of the art parametric design and scripting cultures in the architecture industry. It was found that use of well-designed components and subcomponents with product information provides a virtual identity card within the BIM file. It allows next designer to explore the use of demounted materials and help replace broken components easily and faster.

From MADASTER, it is known how dashboards can help track circularity and environmental impacts throughout the building process to completion. Hence, Active procurement (secondary material) must be combined with an Active feedback system (on circularity and environmental impacts).

Chapter 5. Innovation concept

From the literature review in Chapter 2, Chapter 3 and Chapter 4, information ranging from the necessary indicators, required parameters for material bank and current practices have been gathered. This chapter summarises the fall backs and proposes method of assessment with additional assessment techniques that enriches the decision making during a design process.

5.1 Design brief for the Assessment Framework

From the previous study following indicators need to be analyzed simultaneously -

1. MCI is required to check the circular flow of materials. Also, the variables such as virgin, recycled, reused, recyclable and reusable content, and unrecoverable waste should be known.

2. Embodied CO_2 should be calculated to compare the reduction in impact compared to a linearly flowing material.

3. Cost of the product shall ensure that circularly flowing material is more affordable than compared to a use and throw model.

4. Technical performance of the element such as U value, Thermal conductivity and Acoustic velocity, shall ensure thermally insulated and quiet indoors.

5. To ensure transformation potential, heavy objects with low lifespan should be avoided. Assembling and disassembling of these objects are less feasible.

The framework should also allow the following -

- Enable access to available material database at early design stage.

- Should be easy to use by architects and engineers.

- Framework should help make a sustainable choice.

- All the necessary information to reduce environmental impacts should be accessible and transparent.

In next section the design development of the tool is discussed that could enable the agendas set above and in Chapter 6 the functioning of the tool is tested with a design exercise.

Software utilized

To demonstrate the workability of the tool that would enable the objectives of this research. A material database was created and assessed using Microsoft Excel. And to enable the connection between Excel database and design environment Rhino 6+Grasshopper is used. Hence, Rhinoceros becomes the platform for visualizing the 3D models. To provide a material explorer, Design Explorer (Core studio, 2019) is used as it can provide filtering based on various variables.

5.2 Assessment Framework

The Assessment Framework consists of five interfaces- 1. Material database in tabular format, 2. Material Explorer, 3. Assessment Dashboard, 4. Digital Design space, 5. Visual script in grasshopper. **Figure 5.2.1** shows the progressive nature of these five interfaces. The Framework is also divided in two stages- 1. Preliminary and 2. Advanced assessment. In sub-sections each of these interfaces are elaborated in detail.

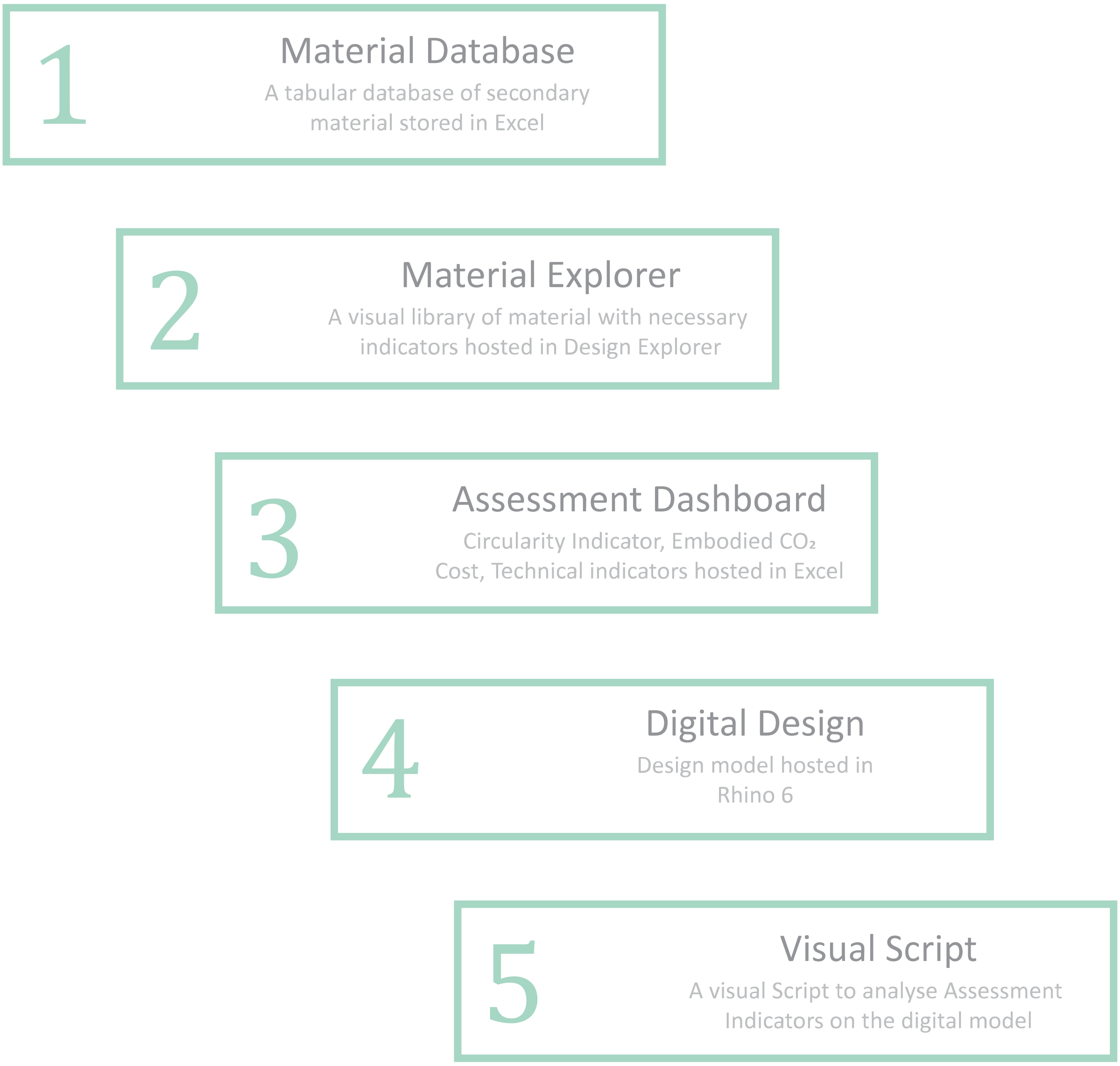


Figure 5.2.1 Assessment Framework with five interfaces, own illustration

From section 2.7.4 it is known that the assessment needs to be divided in two stages because of the complicacy in calculating the circularity rating of the design at early phase. To obtain a precise value of circularity and other indicators dependent on it, the design needs to be analyzed using DfD aspects. This can be done digitally as done in (Denis et al., 2017a). In their study they used life expectancy to avoid the use of materials that have shorter lifespan than the lifespan of the building. But, in section 2.5.1 it was studied that there are 8 DfD aspects and sub-aspects to determine the transformability of a building. Assessing these factors at early design phase is not considered a practical option in this thesis. Hence, to simplify the process and still have an idea of sustainable choices at early stage 'actively', Preliminary Assessment is done. Preliminary assessment is done with an assumption that all the components of the design are 100% reusable if their lifespan is more than the lifespan of the building otherwise they are considered to be recycled at EOL. Whereas in Advanced Assessment a knowledge model is prepared to check the disassembly potential of various components. This knowledge model is explained in section 2.7.2.

5.2.1 Material database

To document all the necessary labels a material database or material 'passport' needs to be created. This can be done in many ways, such as MySQL, Relational Database Management System, Pen & paper or Microsoft Excel. An SQL database is the most recommended option to create a database of architectural materials as also mentioned by Jaco (Appendix 2). But for a small data and minimum number of labels, Excel is suitable. It is also easier to understand by architects and engineers. The main labels used in the material database and in this study are shown in Appendix 3.

Tracing and documentation process

In Appendix 3 the database that was created is shown. The tables that were created and their relationship are explained below-

1. **Material info-** This consisted of standard properties of different architectural material. It consists of Density, Costs, Virgin content, Recycling efficiency, embodied CO_2 of the recycling process, Location of if sourced virgin etc. This table is used set default values in other tables.

2. **Distance calc-** This table listed seven different locations within Netherlands and their distance from one another. It also consisted of User inputs like location of design project and expected lifetime.

3. **Lifecycle management-** This table consist all major data to calculate MCI, embodied CO_2 and Cost. All the variables are calculated for each nested component. And as the name suggests, various life cycles of each nested element can be traced here.

4. **Main Dataset-** This table is the center of all available components filtered with which lifecycle they are in. Life cycle management and Main dataset go hand in hand. Once an element it listed with product code, material and dimensions in this table, then life cycles are tracked in Lifecycle management table. Then, lifecycle level is chosen from Life cycle management table and MCI, Embodied CO_2 and Cost variables are copied to this table.

5. **Design Dataset-** This is an important table that combines all other tables. Once, the decision is made for which secondary products are needed, the products from Main dataset are then copied in this table. Also, the new components that are required to be evaluated among the secondary ones are evaluated in this table. To evaluate the new components, materiality has to be defined in Rhinoceros and all other variables are set by default. This will be explained further in section 5.2.5.

Inputs required from the architect/engineer before starting the Preliminary assessment are-

1. Location of the design project

2. Expected use life of the building

To begin with the Preliminary assessment, the product code can be noted down from the Material Explorer and the .3dm file can be imported in the Digital Design interface. The imported 3D model are assigned with the necessary labels to perform the Advanced assessment using the Visual Script.

To assess new materials along with the secondary elements, material of all new elements has to be defined in the Digital Design interface. As shown in This is done by organizing the new material in different layers in Rhinoceros. Then the Visual Script is used to add these material to Design dataset.

5.2.2 Material Explorer

For procuring secondary material an interface was required. This interface enables transparency and filtering based on different variables of assessment criteria. For this purpose Design Explorer is used. It allows to document various design iterations hosted in an online platform. A Grasshopper plugin- Colibri is used to create the database to feed design explorer. The interface gives an opportunity to add an image and a 3D model for each iteration accompanied by custom parameters to allow filtering between multiple iterations. **Figure 5.2.2** shows the proposed interface to view the available (hypothetical) secondary material.

In **Figure 5.2.2** a) displays all the available materials with their respective parameter displayed on the top ribbon. The bottom ribbon shows the different iterations created in a circular icon with an image inside. To view a bigger picture, the circular icon can be clicked which transit to the details of that iteration. Also, By clicking & dragging the domain at the top ribbon a range of values can be shortlisted within different parameters. In b) domain is set for length and height which result in five iterations that lie within those values. Once satisfied with either of them, user can click & select any one of them to view its 3D geometry as shown in c). This interface is tested to procure secondary material in Chapter 6.

The labels that are included to filter material are-

1. Product code
2. Length
3. Height
4. Depth
5. MCI
6. % of virgin content
7. % recycled content
8. % recyclable content
9. % reusable content
10. Total unrecoverable waste (kg)
11. Embodied CO_2
12. Cost
13. Life expectancy
14. U value

This interface is developed for a hypothetical set of windows. It was created using a custom Grasshopper script shown in 6.3Appendix 5. This interface is accompanied by a set of 3D models which can be used to visualize potential reuse. The names of the 3D files are the product codes displayed in the Material explorer. Hence, making it easier to find the right model. The 3D models are assigned with the labels shown above.

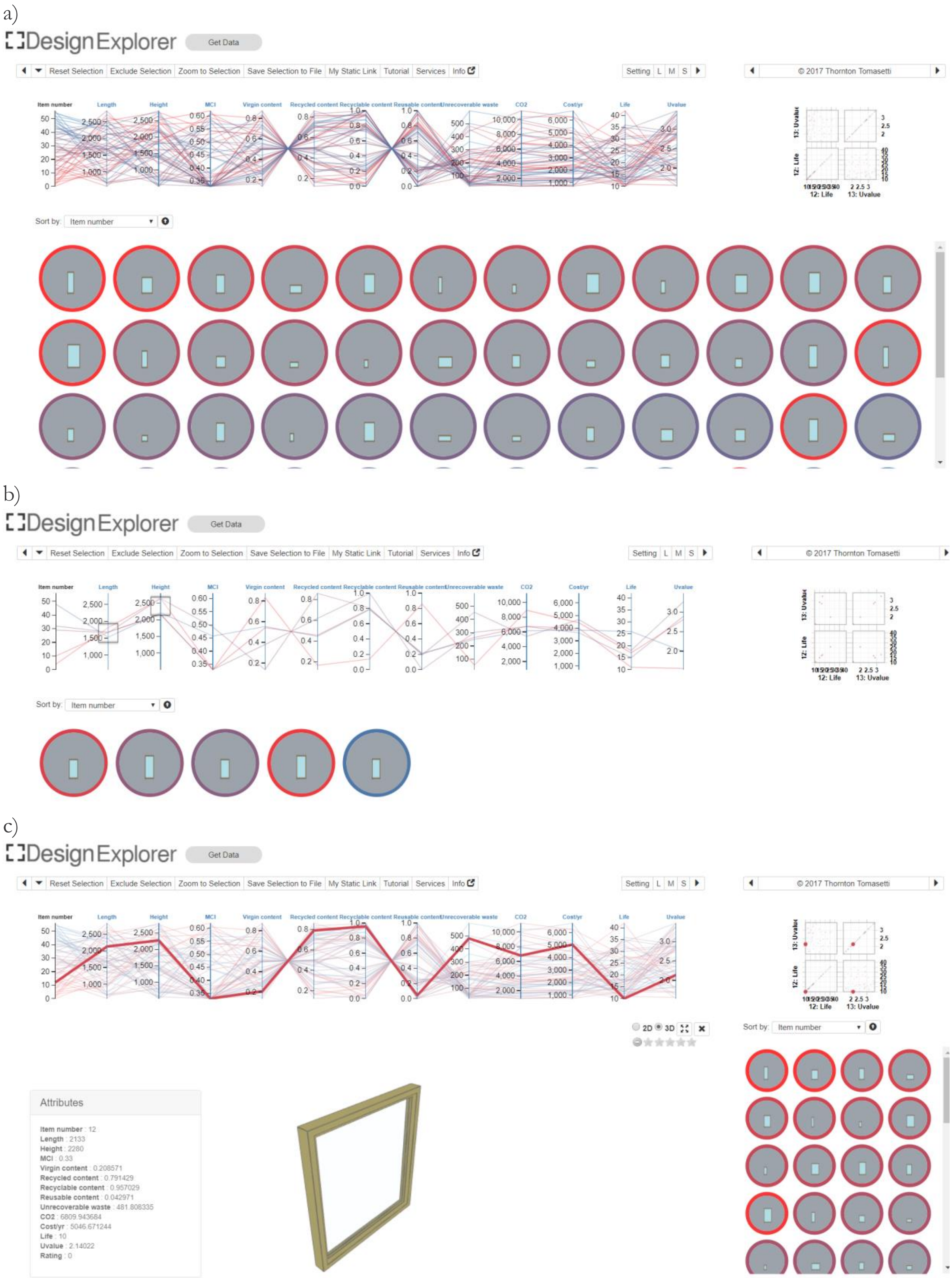


Figure 5.2.2 Material Explorer for secondary windows using Design Explorer from Core studio; a) before applying filters, b) after applying filters for length and height, c) 3D view of the desired window.

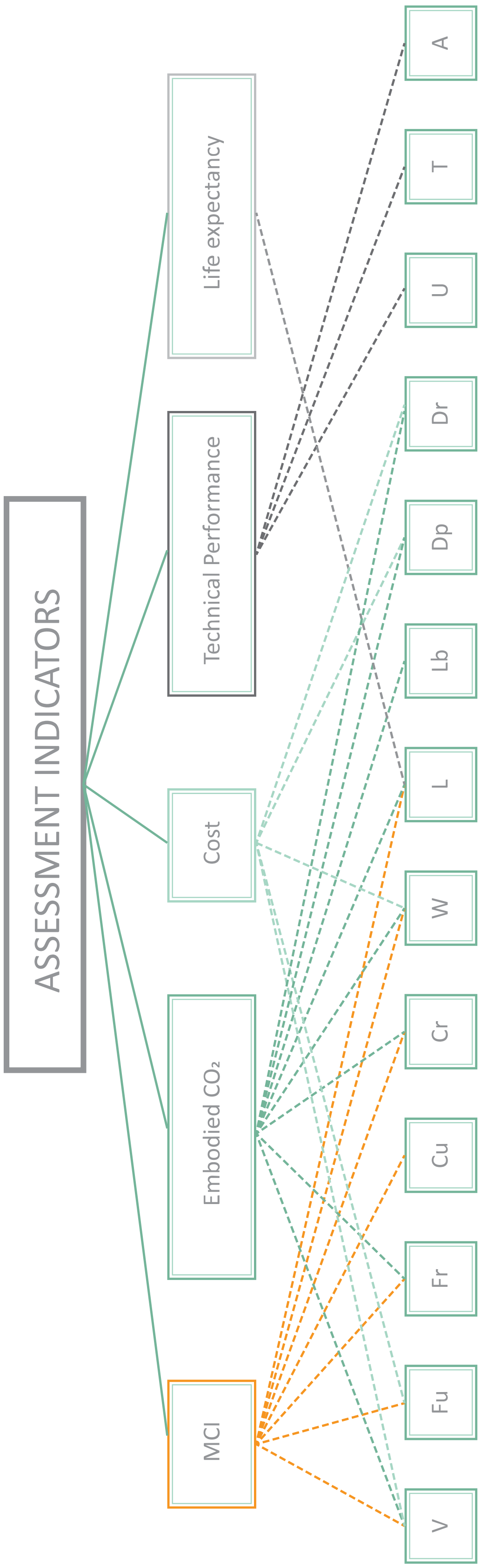


Figure 5.2.3 Dependency between 5 key indicators and 13 sub-indicators

5.2.3 Assessment Dashboard

The assessment Dashboard is an aggregated display of the keys indicators to make a sustainable choice while procuring secondary material. There are 5 main indicators and 13 sub-indicators proposed based on the previous study.

Figure 5.2.3 shows the dependency of the 5 key indicators with sub-indicators. The sub-indicators are defined in **Table 5.2.1**.

	Symbol	Definition
1	V	Virgin content
2	Fu	Reused content
3	Fr	Recycled content
4	Cu	Reusable content
5	Cr	Reusable content
6	W	Unrecoverable waste
7	L	Life expectancy of the material
8	Lb	Expected use life of the building
9	D_p	Distance of the material from project site
10	D_r	Distance of the recycling plant from the project site (assumed 10km)
11	U	U-value
12	T	Thermal conductivity
13	A	Acoustic velocity

Table 5.2.1 Sub-indicators for the Assessment dashboard

All the sub-indicators that are associated with MCI are also affecting the results of other indicators. This way it allows to analyse how much environmental impact is caused due to a virgin or secondary material.

Cost calculation is limited to the mass of virgin and reused content, and transportation cost to the project site, recycling plant and unrecoverable waste. This boundary condition was created to differentiate between the dominating transportation cost.

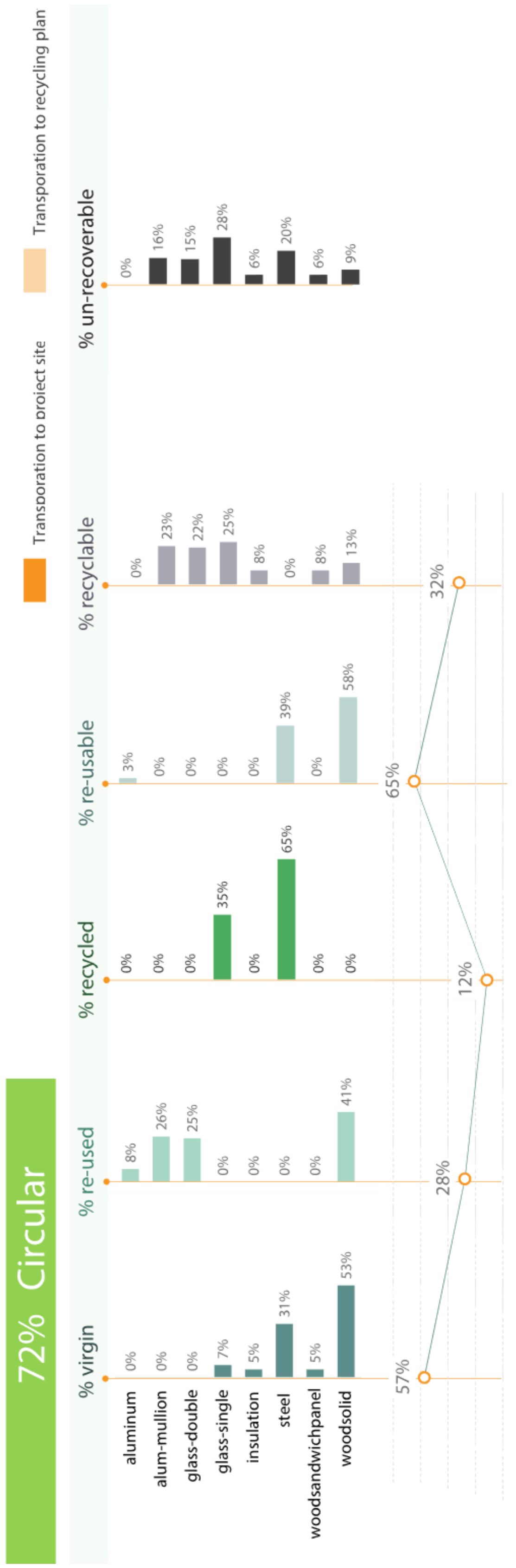


Table 5.2.2 MCI variables used in the Assessment Dashboard

Technical performance indicator is not directly affecting the results of other indicators but is essential to be known to analyse energy performance of the whole building. These key indicators are further elaborated in following section.

5.2.3.1 Circularity Indicator- MCI

Chapter 2 concluded MCI can effectively measure circularity of any material. It measures how much material is flowing in a linear fashion and favours reuse over recycling. It also considers manufacture of durable products through the Utility factor.

Out of all the MCI variables described in section 2.6.1, 6 key sub-indicators are identified essential to determine the circularity of any material. These 6 sub-indicators can be categorised into two phases of life – Production and End of use. % of virgin, recycled and reused content is considered at production phase, whereas % recyclable, reusable and unrecoverable waste determines how much amount of material can return as secondary raw material. Unrecoverable waste also considers how much waste was generated in the recycling process of the feedstock as well as recycling process at the end of life.

Table 5.2.2 shows the composition of MCI variables in the Assessment Dashboard. The horizontal axis defines how many types of material are present for assessment. MCI variables are assigned for all the material. In the scatter chart below, MCI variables are defined for all the materials combined. 57% of the material is virgin, 28% of the material is reused (secondary), 12% of the material is recycled content. Whereas at end of use phase 65% of the material is reusable and 32 % of the material can be recycled. Unrecoverable waste illustrates which material creates maximum amount of waste among all other materials. For example, Glass-single creates 28% of unrecoverable waste. This is due to the fact that it has a 35% of

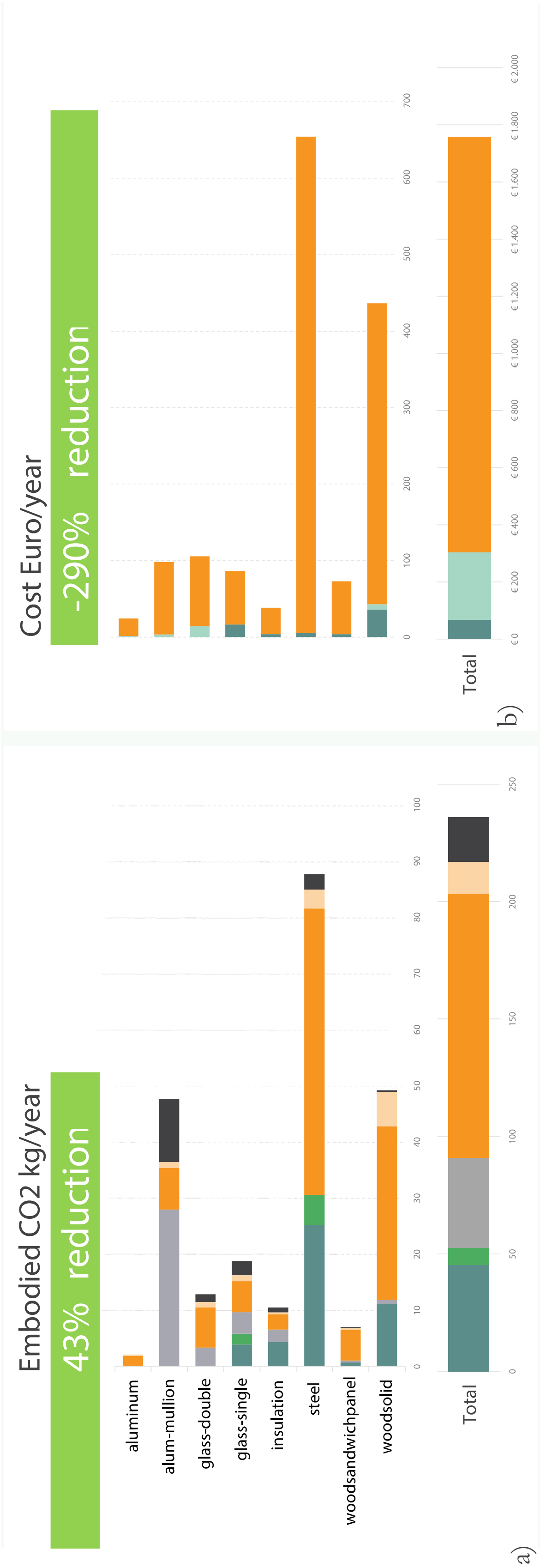


Table 5.2.3 Embodied CO_2 and Cost calculation for Assessment Dashboard

the total recycled content and 22% of the material will be recycled at end of use phase. On the top of the chart, circularity value of all the materials combined is displayed. This is since even though 57% of the material comes from virgin sources, 65% of all materials are reusable at end of use phase.

5.2.3.2 Embodied CO_2

Using simplified boundary conditions as shown in **Figure 2.7.5**. embodied CO_2 is calculated. The horizontal axis of the chart shown in **Table 5.2.3** a) defines the contribution of various materials in the total embodied CO_2 below shown as a stacked bar chart. The stacked bar chart shows how much CO_2 is generated due to MCI variables as well as transportation.

Almost half of the embodied CO_2 is generated due to the transportation of virgin or reused of material to the project site. Whereas only small proportion of the impact is due to the transportation to recycling facility (this is assumed to be within 10km from the project site). Almost 16% of the impact is due to recycling process at the end of use phase. This can be reduced by choosing products with reusable material at end of use phase. To further reduce the impact materials can be identified that are coming for far distances. In this case steel is contributing maximum of CO_2 due to travel. Hence, while choosing materials through Material Explorer, a domain can set to filter products based on distance from the project site. Although this parameter was not added in the current interface.

The top ribbon gives a comparative value of embodied CO_2 that would have been generated, if all the materials were virgin and designed to be completely recycled at the EOL.

5.2.3.3 Economic parameter

This parameter is influenced by whether the product is new or re-used, and how far it must

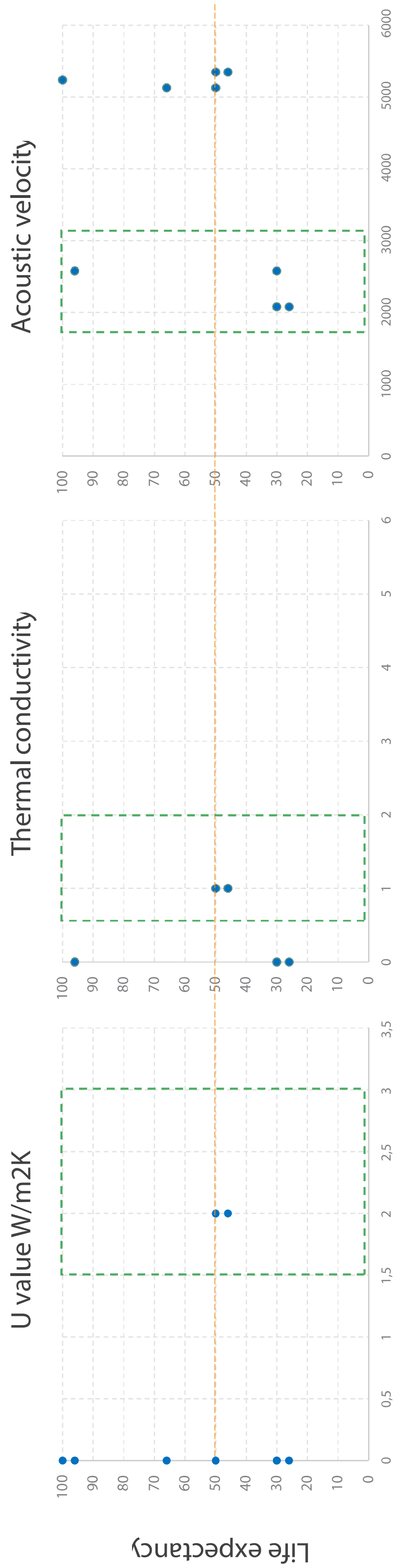


Table 5.2.4 Thermal and acoustic performance v/s life expectancy

travel to reach the project site and to the recycling plant at EOL. This is calculated per year expected use of the building. This makes it easier to conduct fair comparison with buildings that are designed to last longer

or shorter. If the bill of materials is constant for a building that is expected to last shorter, then the cost per years for the project would be more than the building of longer lifespan with the same amount of material.

The chart shown in **Table 5.2.3**, the horizontal axis illustrates the cost of various material and how much of that cost is due to the virgin, recycled, reused, and transportation. The cost is dominated by the transportation of steel to the project site. Steel constitutes 35% of the total virgin mass and hence, also participates in the maximum cost for transportation. It is not necessary that it is coming from a farther distance compared to other secondary or virgin sources.

The total cost of the building material per year of the expected use is shown as stacked bar chart in the ribbon below. This illustrates how much of the cost is due to the total virgin and reused content in the building, the cost of sending material to landfill and transportation costs. The total cost per year is then compared with a cost of a linearly flowing virgin equivalent. Where 100% of the material is expected to go to recycling. In the example shown, the cost of using virgin and secondary sources combined is almost 3 times more expensive. This is because cost of transportation is dominating. To optimise the cost, it will be ideal to choose materials that available locally virgin or secondary.

Even though the cost of material is a fraction of the total cost of building ownership, landfill costs are expected to drive the market and hence it was important to consider this as one of the key indicators. In the illustrates example, the cost of landfill is hypothetically considered similar to the cost of virgin material. With change in policy and new regulations, this assumed value can be changed for more accurate approximation.

5.2.3.4 Technical Performance

Tested values of the thermal and acoustic performance of a product can be analysed this indicator. To ensure high energy efficiency, the exterior envelope of the building should have a U-value lower than 1.5 W/m². Also, products with high thermal conductivity should have minimum thermal bridging with the exterior envelope. In section 3.6.1 it was concluded that operation cost of the building is more than the cost of material. Hence, designing high performing building envelope is essential.

High performance can be assured in two ways. Firstly, choosing products that have best U-value and engineering the details that allow thermal break. In case of existing and older building material U-value of products does not lie between the expected range. However, to still ensure reuse of these material, they can be engineered to perform better. For example, two windows of same size and U-value can be overlapped to form a cavity façade, that could lower the heating loads of the building.

In **Table 5.2.4** U-value, Thermal conductivity and Acoustic velocity are plotted against life expectancy. High performing products with higher life expectancy are ideal to be used for the external envelope of the building. These materials are plotted in the scatter chart around the horizontal orange axis depicting the use life of the building. At the preliminary stage this should not discourage the procurement of secondary material that are low in performance because these materials can be utilized in space planning also rather than using them for the building envelope. The graphs shown in **Table 5.2.4** is just an indication of how many products are underperforming. Using the Digital design interface and Visual Script 3, the location of these components can be identified in 3D. This way a preliminary check can be done that low performing products that are located on the external façade must be engineered to perform better. This becomes the brief for the designer or engineer to propose a solution for reusing secondary material while ensuring energy efficiency of the design.

Also, since these sub-indicators are plotted against life-expectancy, products with low life expectancy and performance can be avoided. Also, it is more ideal to source material with similar life expectancy so that they can be replaced at the same interval. In case of materials that are functionally independent such as materials used in space, low life expectancy compared to façade element is acceptable. Given that these materials do not disturb the elements with higher life and acting as base element for other components.

5.2.3.5 Life expectancy

Life expectancy of the material can be plotted against the density of each material as shown in **Table 5.2.5** . This enables the user to analyse which materials is reach their EOL before the EOL of the building. Once the materials that requires replacement are identified, they should ideally be light weight to ensure easy disassembly. The element on the farther right should have high life expectancy than the elements on the left side of the graph. The orange horizontal axis defines the expected life time for the building. The materials below this axis would compromise the performance of the building if not replaced on time.

As heavier objects are expected to last longer upgrading them in shorter intervals would be difficult and less likely. Also, heavier components are likely to be assembled first and due to their dependence on other building systems they are less flexible. The graph is an indicator that products that have high density and lower life span should be avoided being further used in the building. It is better to recycle them rather install them in a building for shorter lifetime.

Furthermore, components that are light weight and requires replacement at regular intervals should be checked with DfD aspects to ensure easy transformation without damaging other materials in the context. Likewise, products that have higher life expectancy than the use life of the building should also be easily demountable with minimum wear and tear.

Also, products that reach EOL with the EOL of the building, does not have to be designed demounted in its full form because they will be anyway crushed for recycling or used as backfilling. Although, there demolition should not affect the materials that still can be reused. When life expectancy is visualized in Digital design interface as shown in **Figure 5.2.9**, materials with lower life expectancy can be identified if they are trapped between materials with higher life expectancy. This way the design of the connections between these elements can follow the DfD aspects.

In case demolition is the only possible way to replace certain material, the MCI variables (reusable and recyclable) can be changed. This would change the circularity, embodied CO_2 and Cost indicator which becomes the more accurate approximation of the real life situation. This is referred as Advanced assessment.

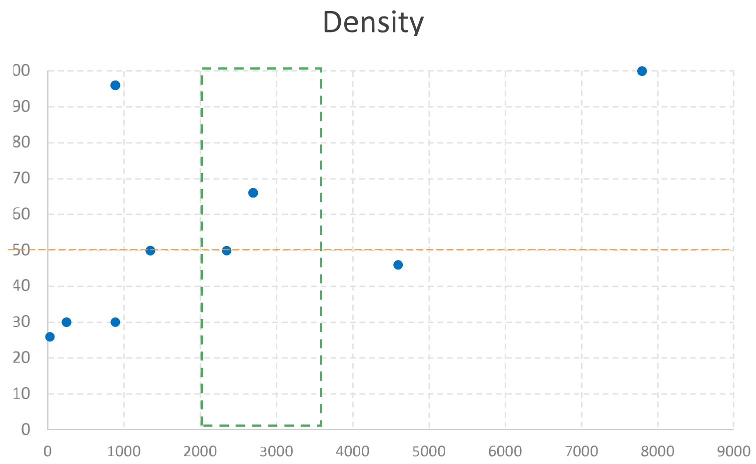


Table 5.2.5 Life expectancy v/s density of the materials

All 5 keys indicators are necessary to analyse in making decisions about using secondary or virgin material. Hence, an aggregated dashboard is proposed to analyse all the indicators simultaneously. This is actively connected with the Material database discussed in section 5.2.1. If there are changes in any of the database structure, it will reflect immediately in the dashboard shown in Table 5.2.6.

Table 5.2.6 Proposed aggregated layout for all 5 indicators forming the Assessment Dashboard

5.2.4 Digital Design

This is an interface where the building is designed and analysed. The material chosen from the material explorer are brought in the 'digital' space with assigned labels discussed in section 5.2.2. **Figure 5.2.4** shows a how a typical interface looks like with assigned labels on the right-hand side. These labels can be analysed using the visual script 3 shown in **Figure 5.2.11**.

To compare virgin sources of the material with the secondary material, the modelled components can be organised under layers named after specific material. These are manually added in the main database with a custom product code. All the necessary labels are set by default through the template in main database.

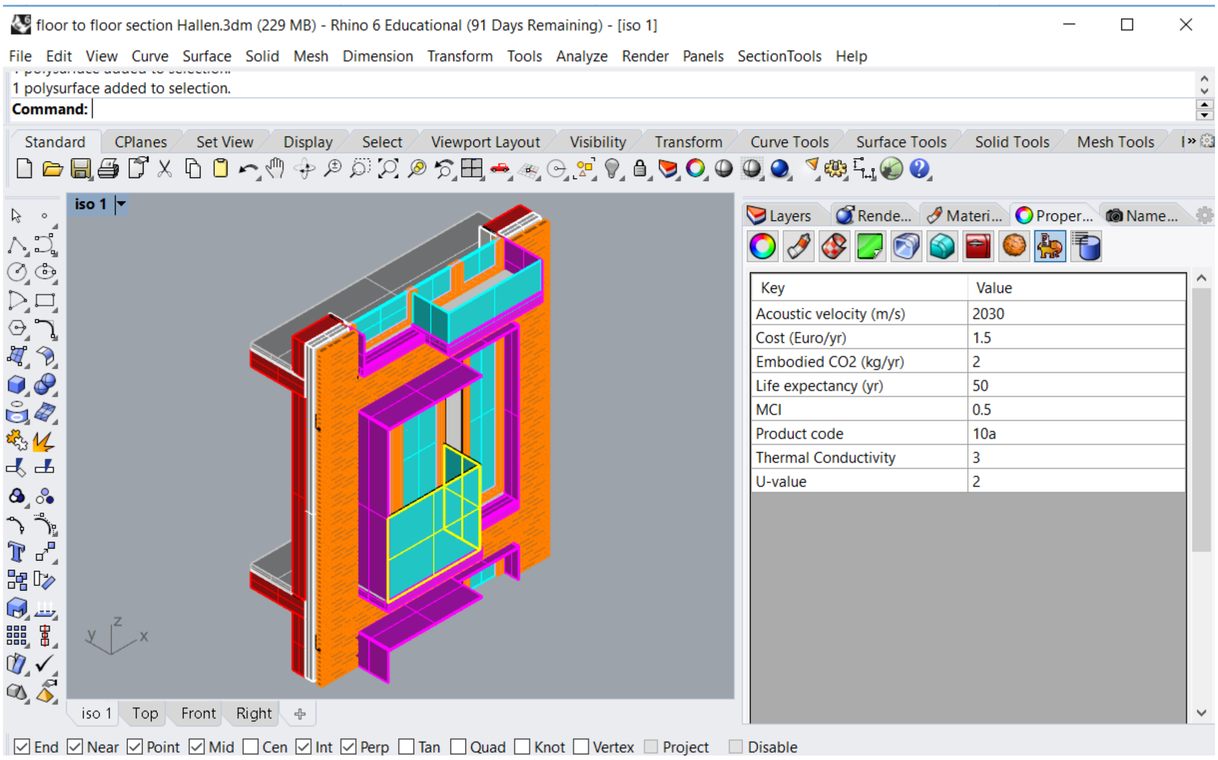


Figure 5.2.4 Digital design interface of Rhino 6 (McNeel) showing components with necessary labels for visual assessment, Source: (GAAGA, 2018)

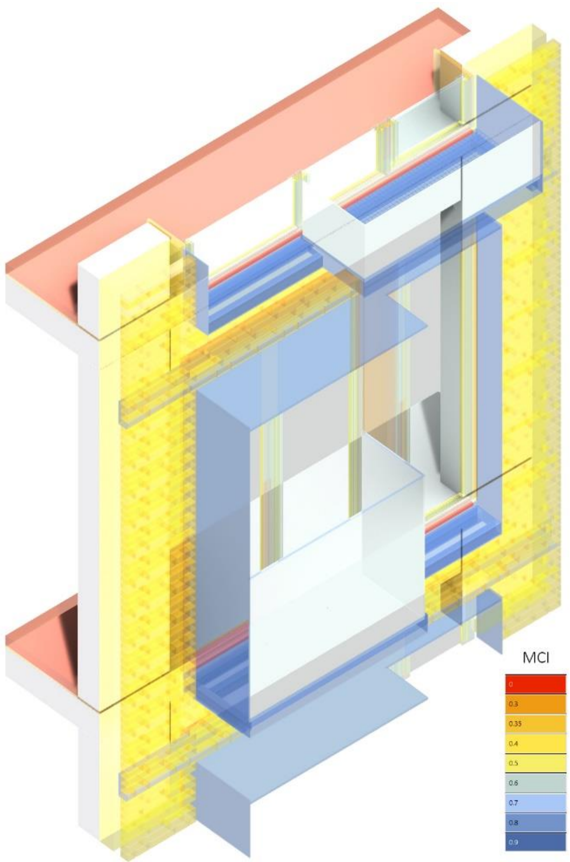


Figure 5.2.5 Visual representation to analyse MCI of various products, Source: own illustration

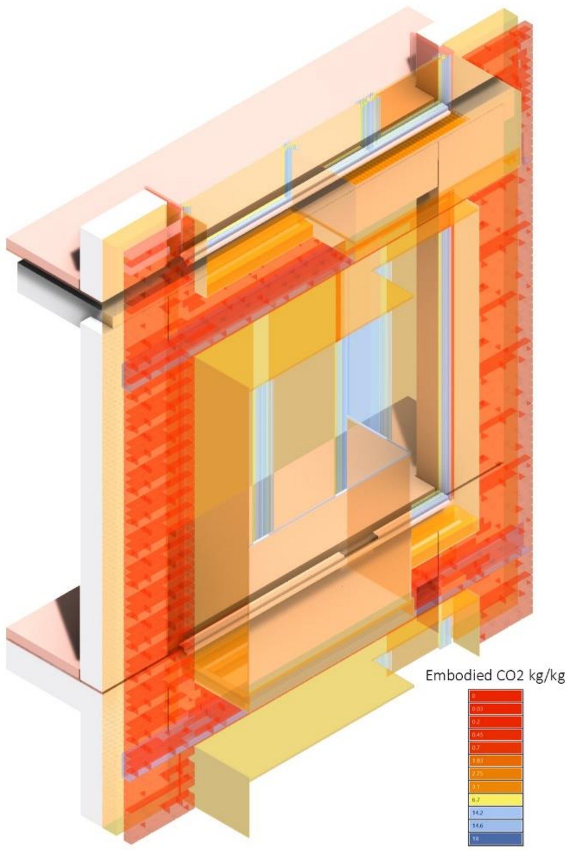


Figure 5.2.6 Visual representation to analyse Embodied CO_2 of various products, Source: own illustration

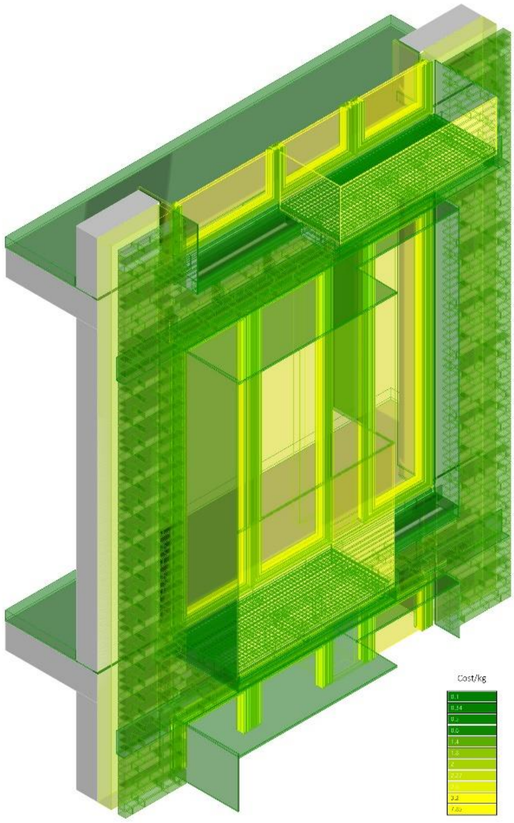


Figure 5.2.7 Cost per year of expected use phase, Source: own illustration

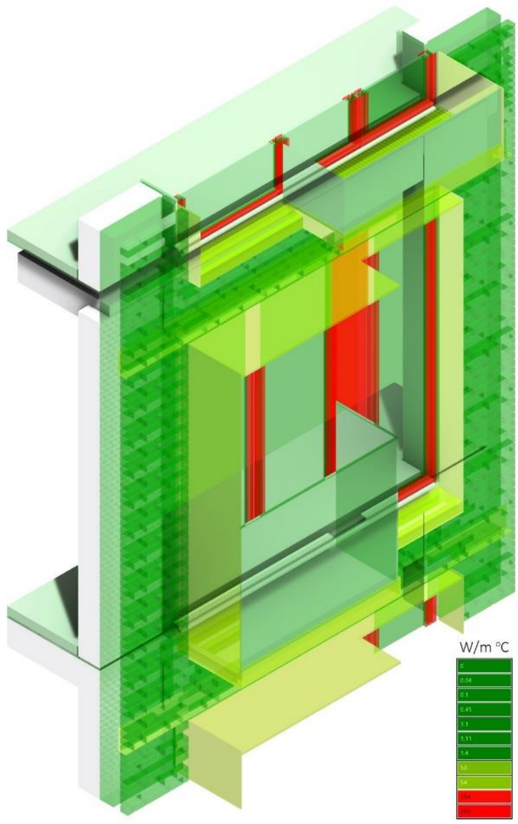


Figure 5.2.8 Thermal conductivity of various material, Source: own illustration

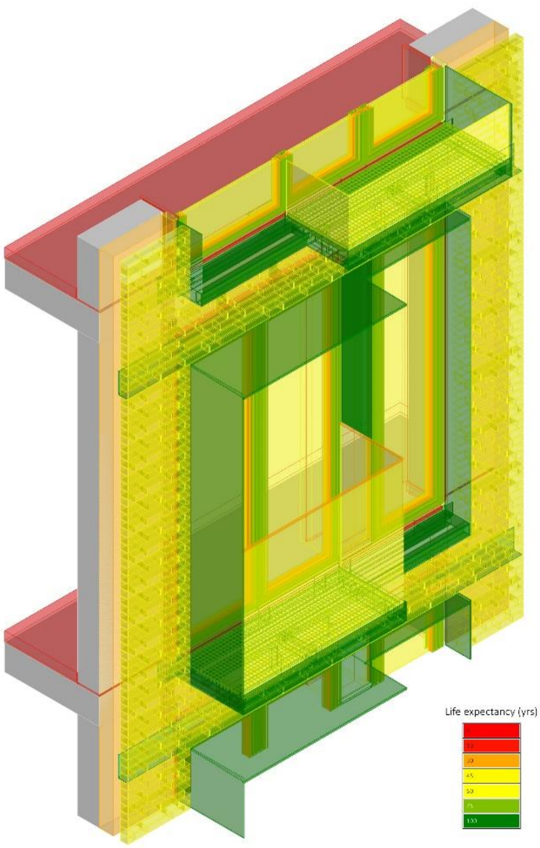


Figure 5.2.9 Life expectancy of various materials, Source: own illustration

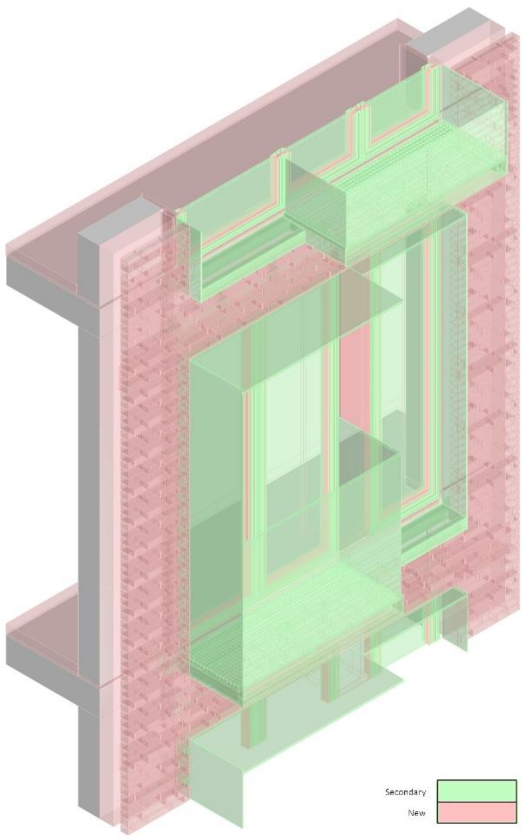


Figure 5.2.10 Secondary versus virgin materials present, Source: own illustration

5.2.5 Visual Script

There are 3 main visual scripts that were developed to make the documentation process time efficient. There are as follows:

1. **Script 1**: Shown in Appendix 5, this script was created for publishing a Material explorer with hypothetical windows. This can be extensively used to document different components of the building if the bill of material is available.

2. **Script 2**: This visual script was created to create a connection between Excel material database and the visual script. The calculations are performed in material database which is then read in the visual script. The labels are then assigned to every iteration of using Colibri. This made the management of various labels efficient.

3. **Script 3**: **Figure 5.2.11** shows the script that is used to preview the values of Assessment indicators in 3D. The domain of values is assigned relative to a customized gradient color pallet. Different gradient can be used for different assessment indicator. **Figure 5.2.5** - **Figure 5.2.10** shows the output in the Digital design interface.

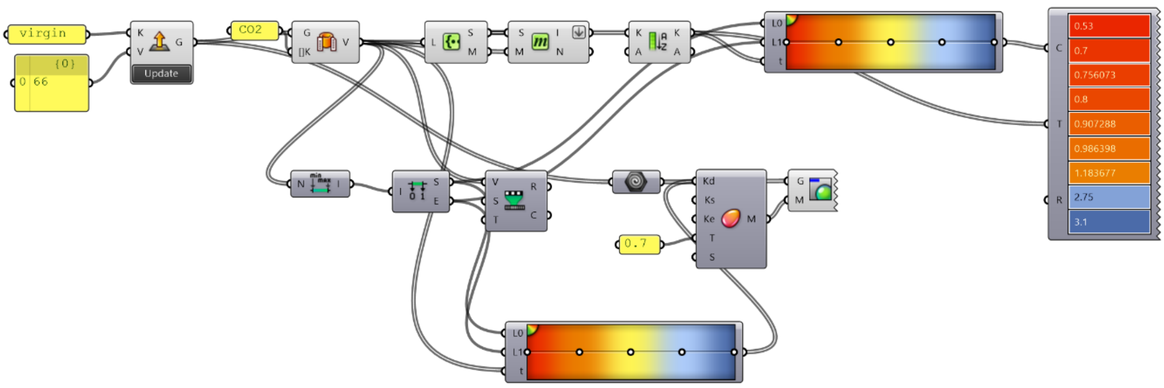


Figure 5.2.11 Script used for visualizing various assessment indicators in 3D Digital design space

Chapter 6. Design case

This Chapter elaborates the working of the Assessment Framework discussed in the previous chapter. To show this effectively, a hypothetical design exercise is scripted in 5 design stages. Preliminary assessment is performed simultaneously at all stages, culminating with Advanced assessment.

6.1 Design assumptions

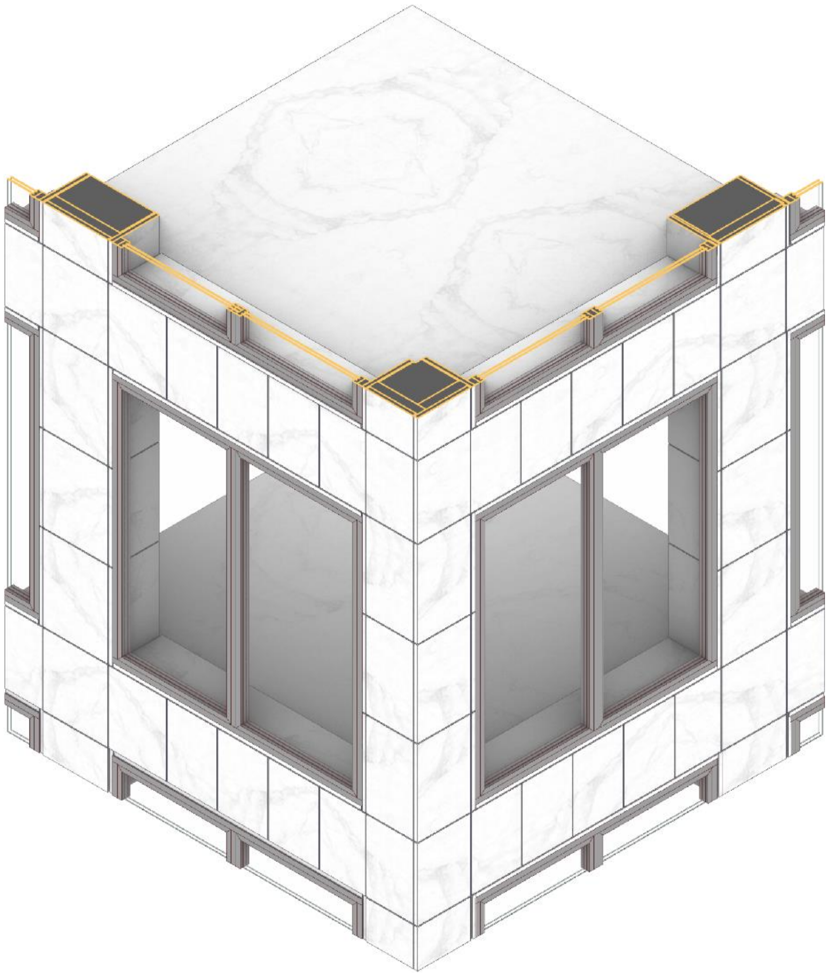
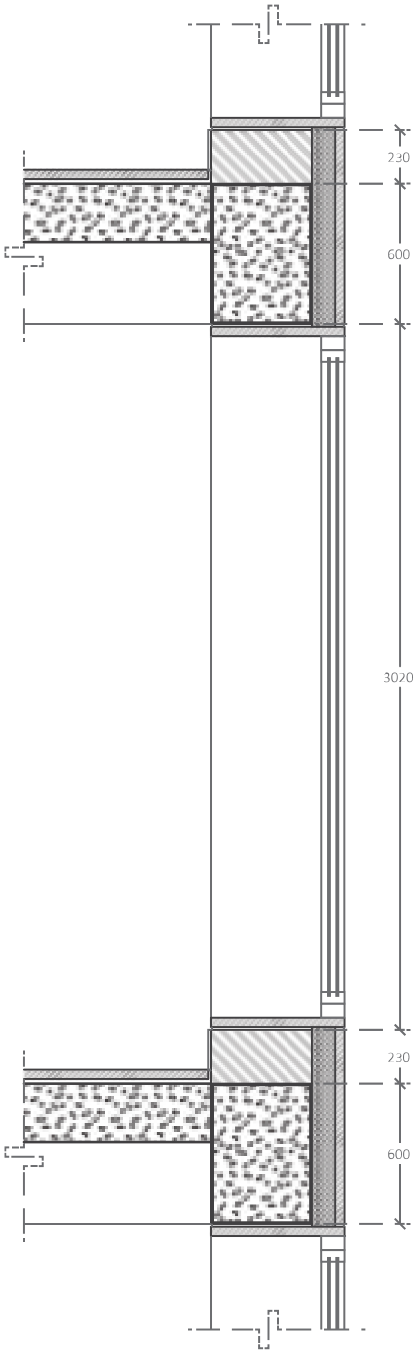


Figure 5.2.1 Current state of a typical office building in the Netherlands

To illustrate a generic wider applicability, a typical old office building is refurbished into an aesthetically pleasing and livable housing. The building is located in Rotterdam and must comply with new regulation to become and energy efficient after the refurbishment. Since, municipality of Rotterdam has also set roadmap to become a circular city, it is relevant to focus on principles of circularity and environmental gains.

Orientation and the typical floor plan of the building is shown in **Figure 6.1.1**. To convert the function of an office building into housing the design of the façade should promote interaction towards outside in contradiction to office culture. **Figure 5.2.1** shows a typical outlook of a office building in Netherlands. The barrier between inside an outside can be removed by adding outdoor spaces such as balconies. The existing design of the façade must be replaced with better insulation. The stone cladding from to façade has to be demolished which can be used as backfilling on site. The glass from the single-glazed window has to be broken down for recycling, whereas the aluminum mullion can reused as a building material for other purposes. The concrete structure and the brick sill can be retained with minimum repair after demolition of other parts.



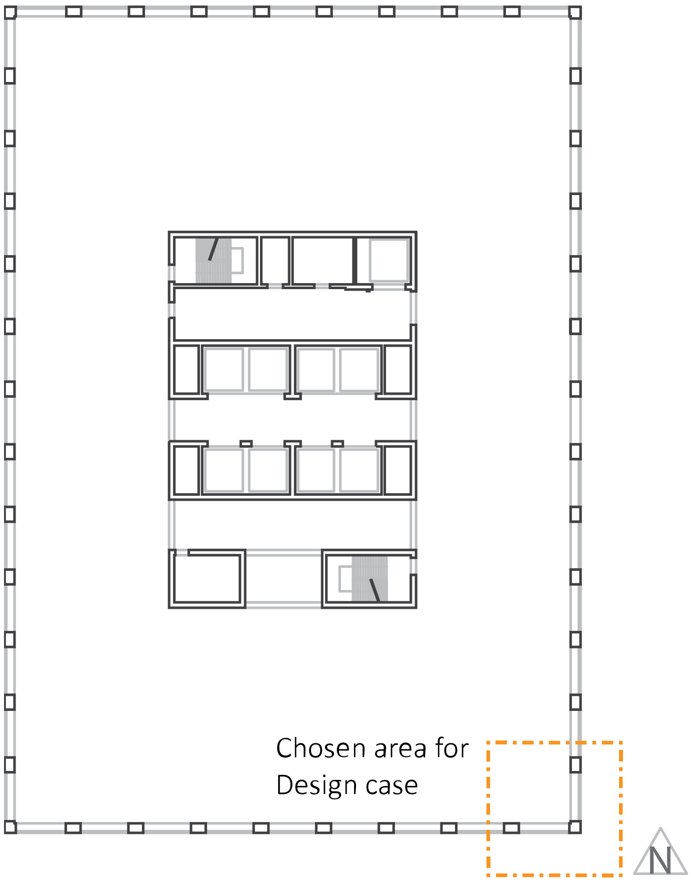


Figure 6.1.1 Typical floor plan the building that needs to be refurbished into a housing, Source: Own illustration

The new design should maximize the heat gain during winter and minimizing over heating during peak summer months. To evaluate this, the south-west corner is chosen. The structure of the building can last for 50 years. Hence, the design of the details should allow for transformation of the parts that would need replacement and maintenance without disturbing other components.

Figure 6.1.2 Typical wall section, Source: Own illustration

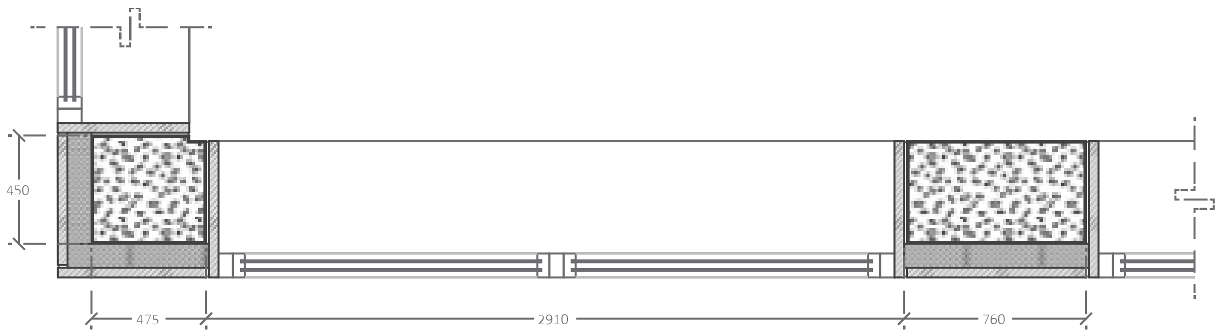


Figure 6.1.3 Typical plan detail of the external structural wall, Source: Own illustration

6.1.1 Stage 1

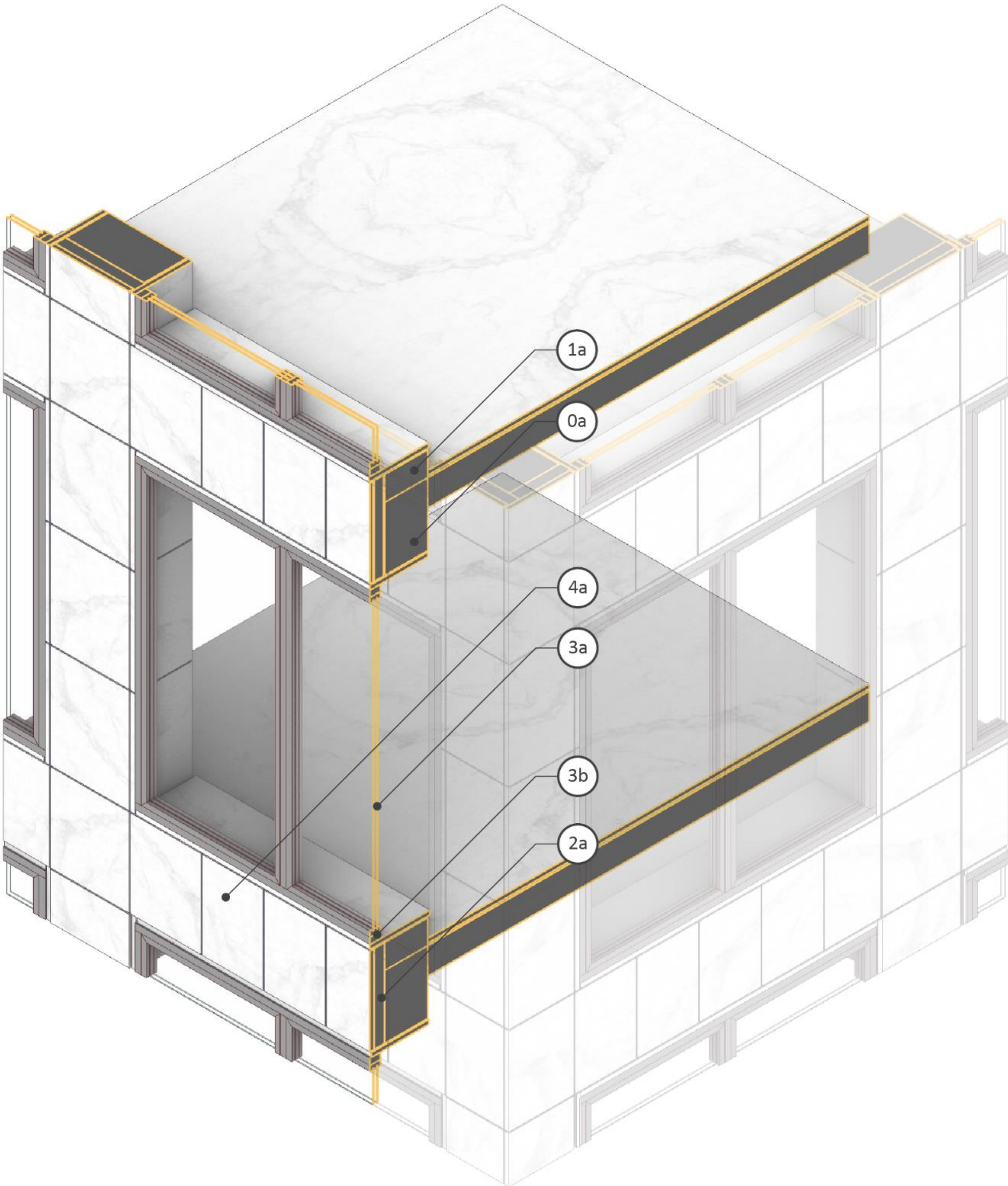


Figure 6.1.4 Chosen corner detail of a typical office building envelope with existing materials

After analysing the bill of materials (**Table 6.1.1**), the results from the assessment dashboard is shown in **Table 6.1.2**

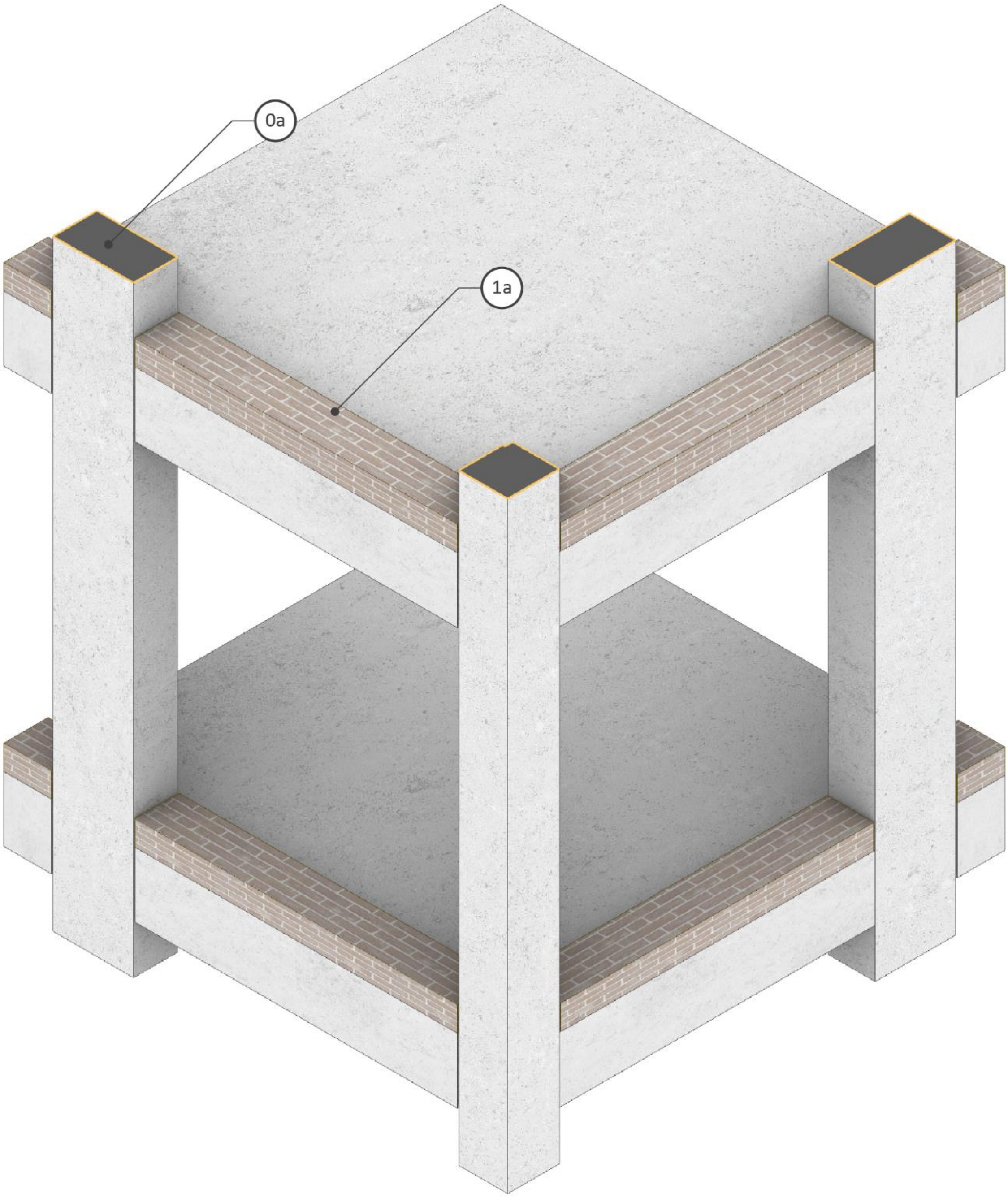


Figure 6.1.5 After removing the material that is recycled and keeping the material that can be reused in further design development.

Product code	NL/Sfb	Material	Mass (kg)	Life expectancy (yr)	MCI	Embodied CO_2/yr	Cost Euro/yr
0a	28.2	Reinforced concrete	33600	100	0.84	2657	8
1a	28.2	Brick	2691	25	0.87	214	18
2a	28.2	Insulation	83	0	0	8	1
3a	31.1	Glass	705	0	0	64	27
3b	31.1	Aluminium	810	50	0.93	145	7
4a	43.1	Stone	10260	1	0	807	41

Table 6.1.1 Simplified list of material considered for Preliminary Assessment

Table 6.1.2 Preliminary assessment results based on the amount of material being reused or recycled at stage 1 of the design process

6.1.2 Stage 2

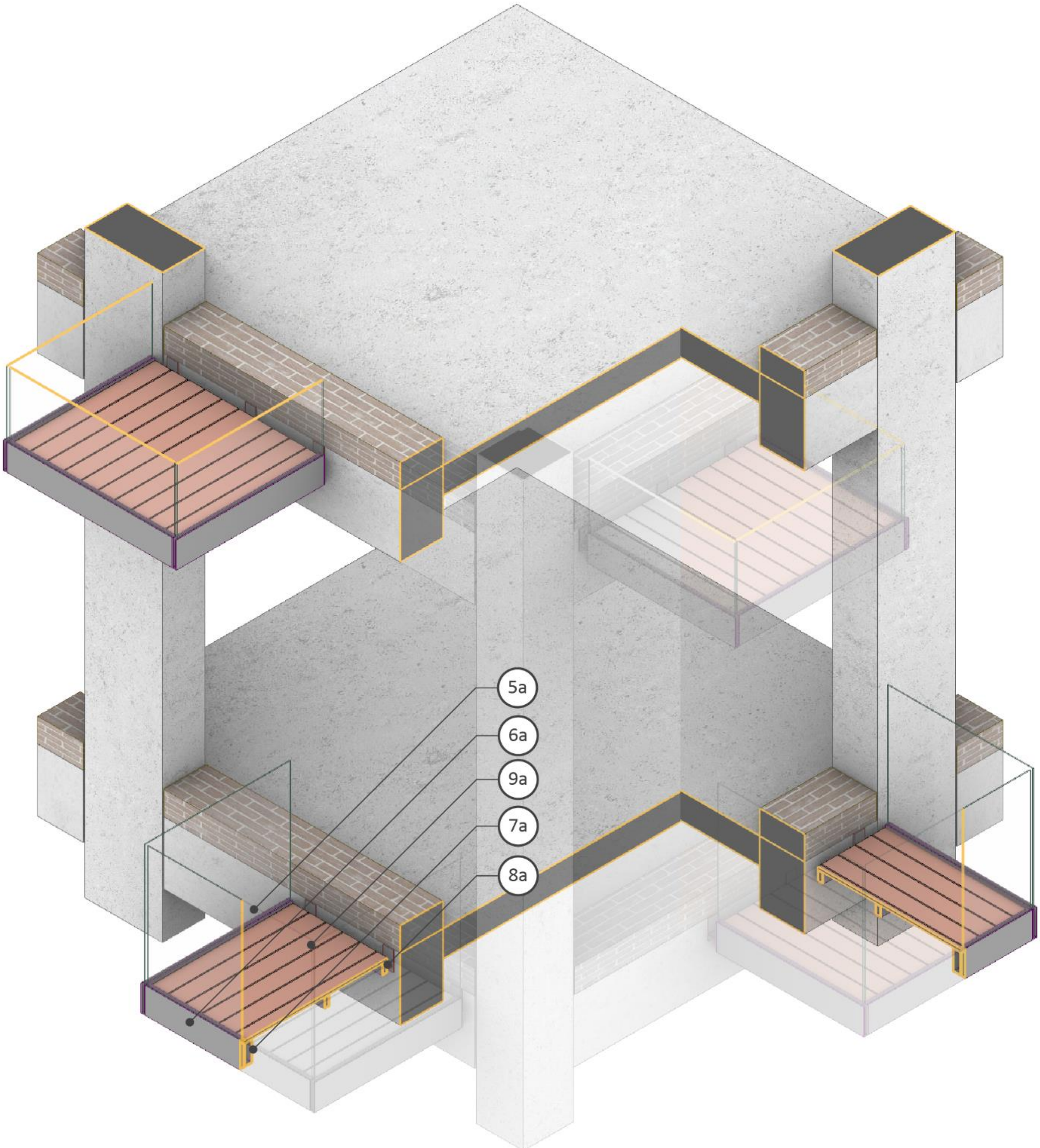


Figure 6.1.6 Adding balconies with use of virgin material at Stage 2 of the design process

Product code	NL/Sfb	Material	Mass (kg)	Life expectancy (yr)	MCI	Embodied CO_2/yr	Cost Euro/yr
5a	31.1	Glass-single	211	50	0.70	210	23
6a	31.2	Steel	280	100	0.67	671	28
7a	31.3	Steel	280	100	0.67	671	28
8a	31.4	Steel	93	100	0.67	335	14
9a	31.1	Wood solid	89	100	0.55	70	7

Table 6.1.3 Bill of material of the virgin material added for balcony at stage 2 of the design process

Table 6.1.4 Preliminary assessment results based on the amount of material being reused or recycled at stage 2 of the design process

6.1.3 Stage 3

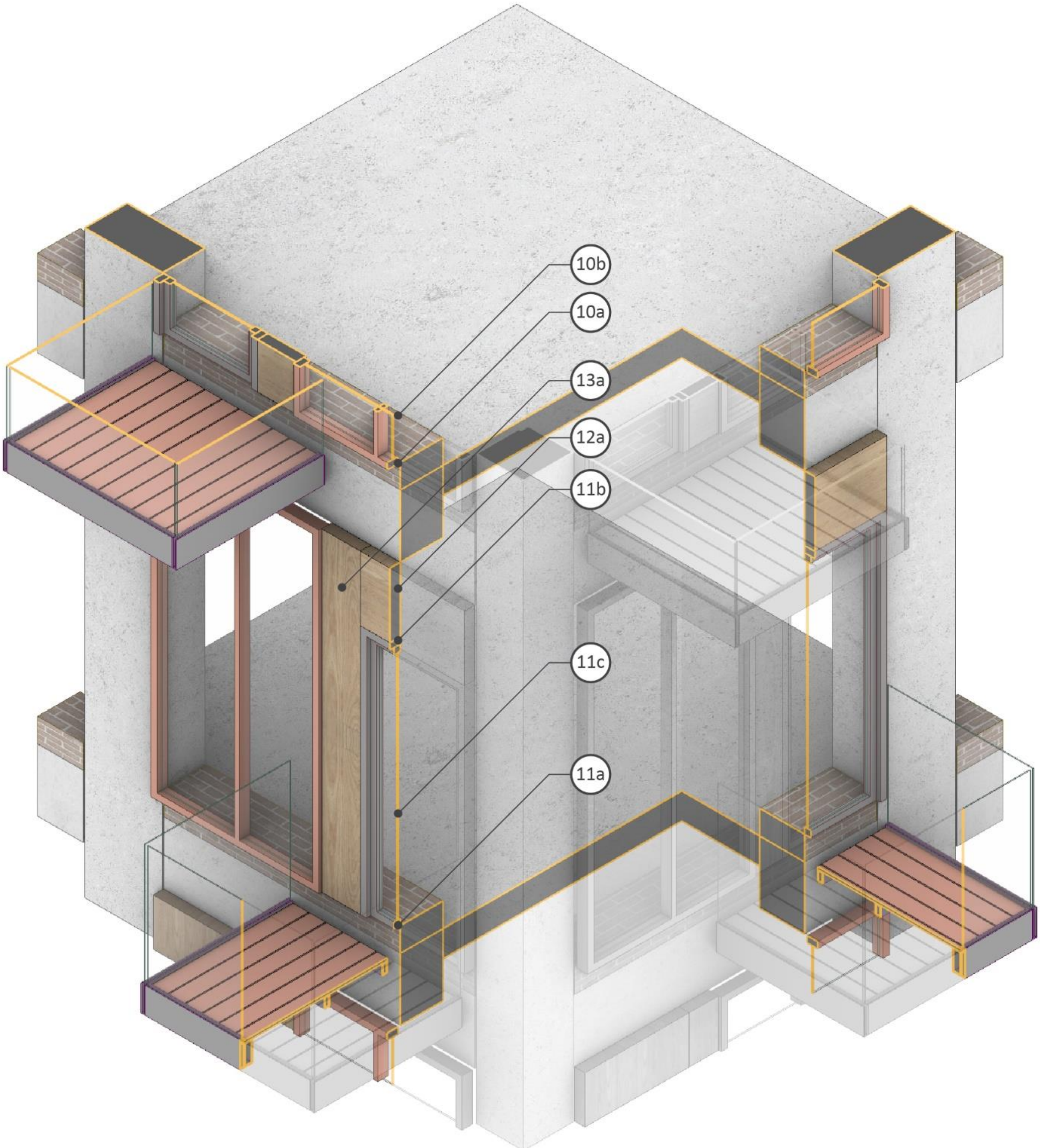


Figure 6.1.7 Stage 3 of the design process with windows, doors and external wall panels.

Product code	NL/Sfb	Material	Mass (kg)	Life expectancy (yr)	MCI	Embodied CO_2/yr	Cost Euro/yr
10a	31.6	Wood solid	106	30	0.84	7	73
11a	31.6	Alum-million	100	50	0.93	25	51
11b	31.7	Alum-million	92	50	0.93	23	47
11c	31.7	Glass-double	184	46	0.95	13	106
12a	31.8	Wood sandwich panel	30	30	0.48	3	31
13a	31.8	Wood sandwich panel	40	30	0.48	4	42

Table 6.1.5 Bill of material of the secondary and virgin material added at stage 3 of the design process

Table 6.1.6 Preliminary assessment results based on the amount of material being reused or recycled at stage 3 of the design process

6.1.4 Stage 4

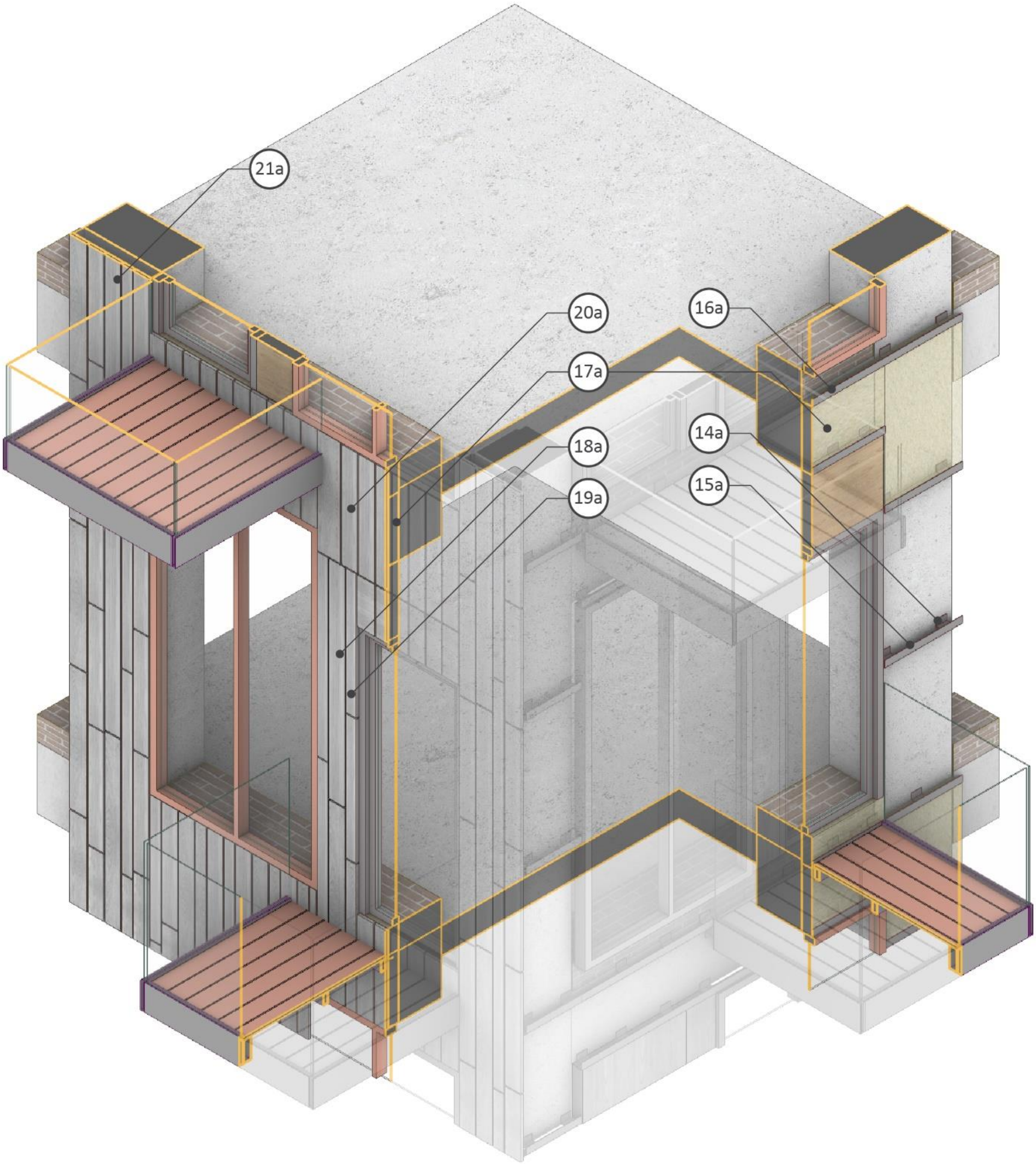


Figure 6.1.8 Stage 4 of the design process with insulation and wooden cladding.

Product code	NL/Sfb	Material	Mass (kg)	Life expectancy (yr)	MCI	Embodied CO_2/yr	Cost Euro/yr
14a	31.9	Aluminium	9	66	1.00	0	4
15a	31.9	Aluminium	10	66	1.00	0	5
16a	31.9	Aluminium	34	66	1.00	1	15
17a	31.9	Insulation	70	26	0.40	11	39
18a	32.1	Wood solid	791	96	0.53	32	297
19a	32.1	Wood solid	32	96	1.00	1	11
20a	32.1	Wood solid	100	96	1.00	3	35
21a	32.1	Wood solid	56	96	1.00	1	20

Table 6.1.7 Bill of material of the secondary and virgin material added at stage 4 of the design process

Table 6.1.8 Preliminary assessment results based on the amount of material being reused or recycled at stage 4 of the design process.

6.1.5 Stage 5

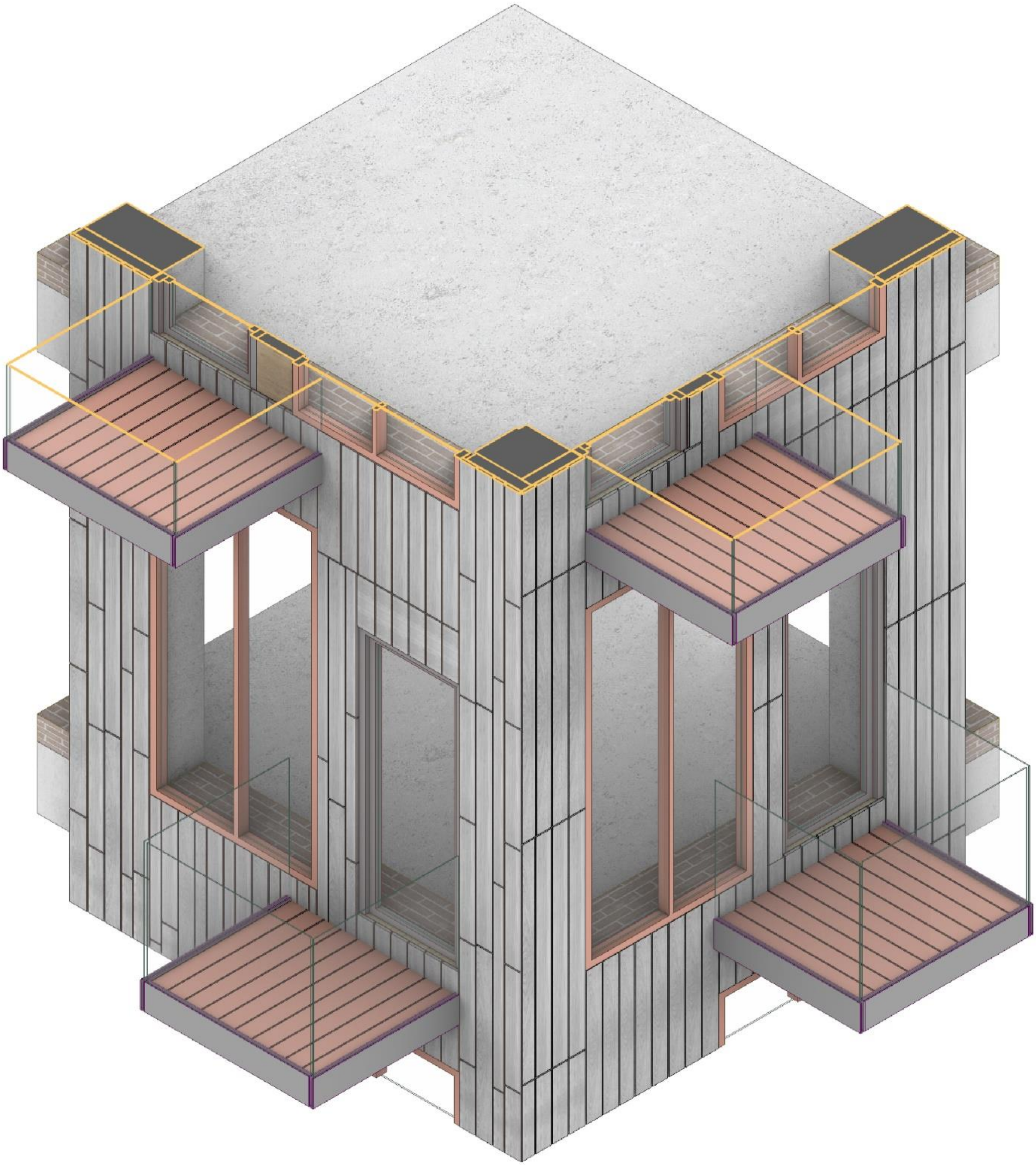


Figure 6.1.9 Final design view with wooden cladding from secondary sources on the left side and virgin sources on the right-hand side.

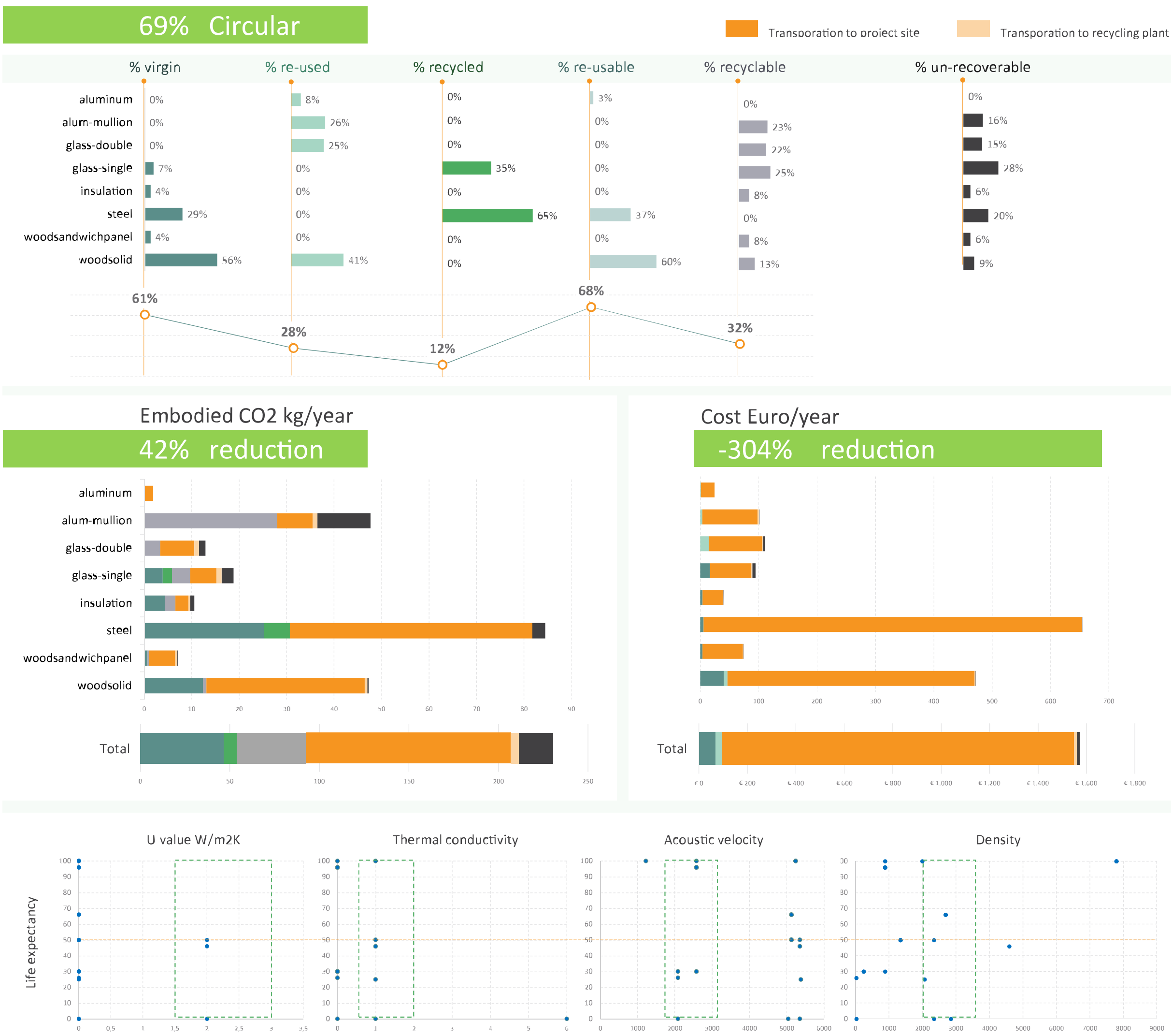


Table 6.1.9 Preliminary assessment of the design without the existing structure.

6.1.6 Discussion

To perform the assessment, a corner floor of the building is chosen for redesign as shown in **Figure 6.1.4**. At stage 1 an assessment is made based on the existing condition of the building. Based on traditional practices, exterior stone cladding, Insulation, glass, aluminum and stone is recycled. Whereas concrete structure and brick sill is considered to last 100 years and is reusable at end of use phase of the building. After the removing these materials the corner looks like **Figure 6.1.5**.

At stage 1 the results from the Assessment dashboard are shown in **Table 6.1.2**. The mass of reused content is dominated by concrete structure at 70%. All the structure is reusable at the end of use phase of the building. The stone is recycled and hence, forms 70% of the total recyclable content. The circularity indicator shows 76% because of absence of virgin content at this stage. 70% of the total mass is reusable and 70% is recyclable. Since, the existing structure is reused without making a new construction, there is a 90% reduction in the embodied CO_2 compared to a virgin equivalent. Also, there is 84% reduction in the cost because no material is sourced yet. The cost is dominated by the amount of reused content and cost of transportation at the EOL.

At stage 2, steel structure is added for the balconies, with glass railing and wooden flooring as shown in **Figure 6.1.6** and the results from the Assessment Dashboard is shown in **Table 6.1.4**. All the components at this stage are sourced virgin. But still it only forms 1% of the total mass of the sample corner. The circularity indicator is still at 76% as most of the virgin material sourced at this stage is reusable at end of use phase. The reduction is embodied CO_2 is estimated at 87% less than a virgin equivalent. Most of the contribution to the CO_2 is because of the steel which is coming from a far distance. Also, the embodied CO_2 of virgin steel contributes almost 10% of the total embodied CO_2. Almost 40% of the embodied CO_2 is due to the recycling process at the EOL. This is dominated by the amount of aluminium that went for recycling even though Aluminium accounts for only 5% of the total recyclable content. This is because of the huge amount energy required of recycling aluminium. To make carbon neutral preliminary assessment, an alternate use of aluminium mullion rather than recycling would have yielded better results.

From stage 1 to stage 2 there is a steep drop in the cost benefits of the design from 84% to 58% respectively. This is dominantly because of the transportation cost of bringing the steel to the project site, forming almost 60% of all costs. Since, the mass of virgin material is 1% it has negligible impact on the cost as well. At this circularity value hasn't changed because mass of the material added is way less than the mass of reused content.

At stage 3 doors, windows and wooden sandwich panel is added on the façade as shown in **Figure 6.1.7**. Wood sandwich panel is coming from virgin sources, whereas, wooden window and aluminium door are secondary as shown in **Table 6.1.6**. There is a further decrease in the CO_2 and cost reductions. This is because of the amount of material that is added are coming from a distance father than its virgin equivalent. All the material used at this stage lie in the desirable region of performance as shown in the table.

At stage 4, insulation, aluminium sub-structure and solid wood cladding is added as shown in **Figure 6.1.8**. The final design of the sample corner is shown in **Figure 6.1.9** Most of the wood can be noticed coming from virgin source as transition to stage 3 happens. The cost reduction is noticed to be decreasing further to 37% because of the domination of the travel distance between the solid wood and project site. Insulation and aluminium contribute least to all the assessment indicators because of the minor share of mass in the total mass of the sample corner. There is no change noticed in the CO_2 reduction benefit because there is more CO_2 footprint for sourcing their virgin equivalent as well as due to high proportion of reused concrete in the assessment.

Stage 5 of the assessment is conducted to review the assessment dashboard without the materials at stage 1. As shown in **Table 6.1.9**, after removing the concrete, aluminium and stone, the three key assessment indicators have drastically changed. This table shows the assessment of the material that is being added for renovation. At 69% circularity, there is 42% reduction in the Embodied CO_2 when compared with a linear model. 61% of the total mass used is coming from virgin sources, with solid wood contributing 56% of this weight. Only 28% of the mass is coming from secondary sources. 68% of the total weight in the sample corner is reusable at end of use phase of the building and rest can be recycled. The unrecoverable waste generated at EOL contributed 10% of the total embodied CO_2. 42% reduction in embodied CO_2 is noticed overall. Most of which is dominated by the virgin content and transportation to project site.

If the final design is taken forward to be built, it will cost 3 times more than a virgin equivalent. But the cost saved in reusing concrete structure resulted in 37% savings as seen in Stage 4. If all the materials were virgin it would not cost extra but there would be also no environmental benefits.

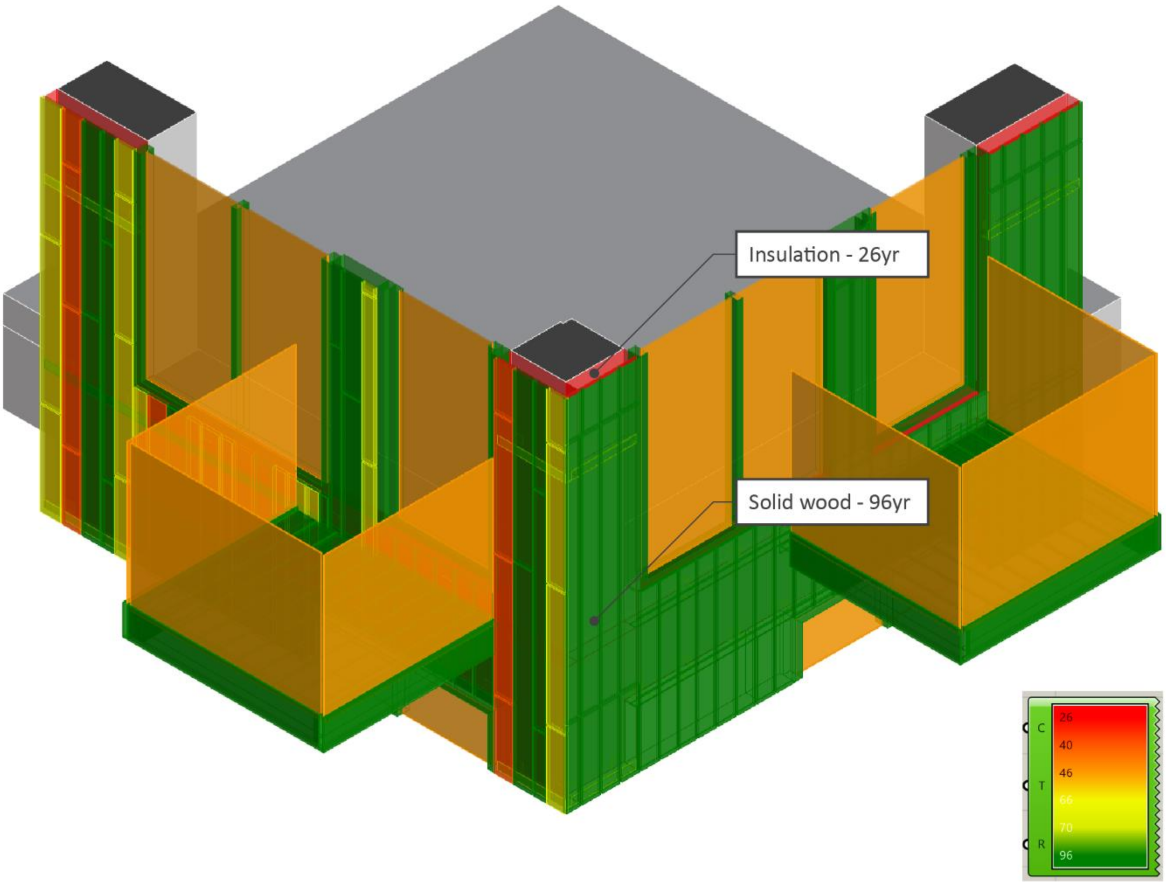


Figure 6.1.10 Life expectancy of various materials visualised using Visual script 3.

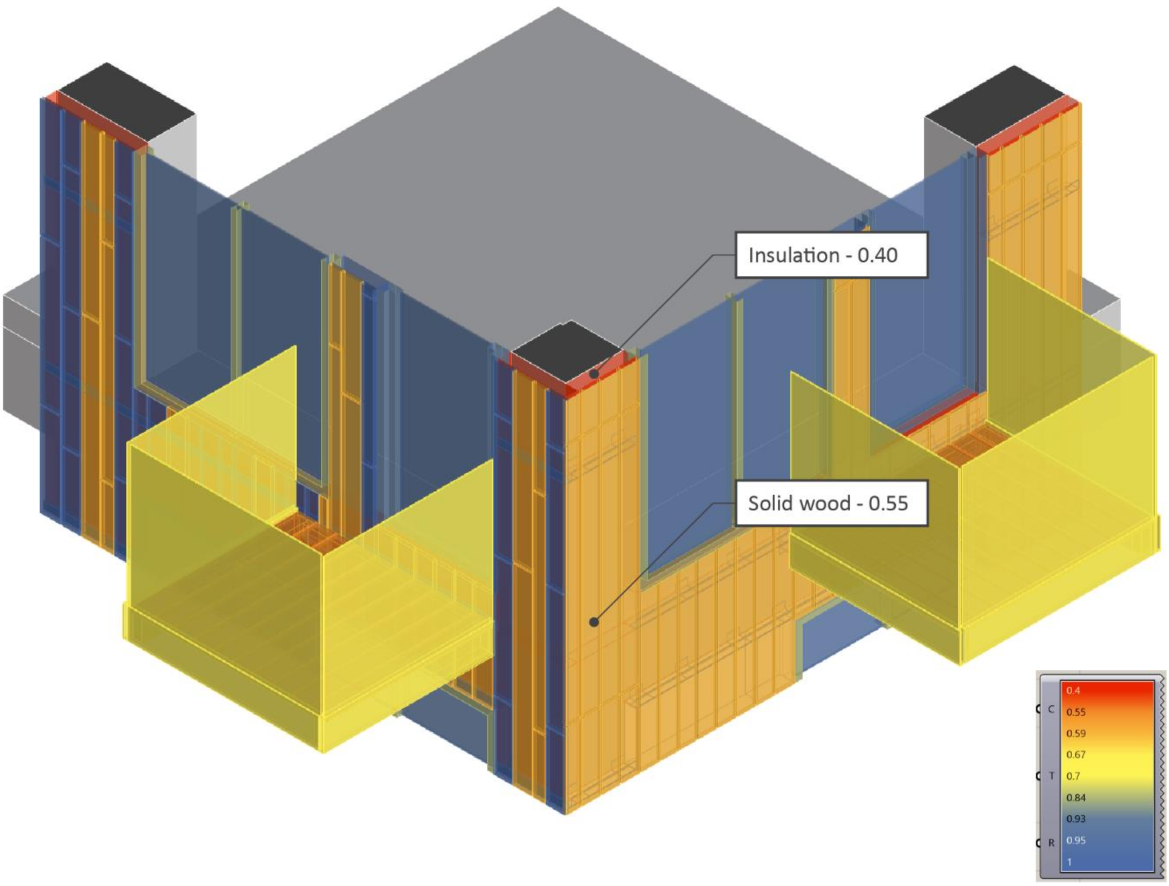


Figure 6.1.11 MCI values of different components in the building.

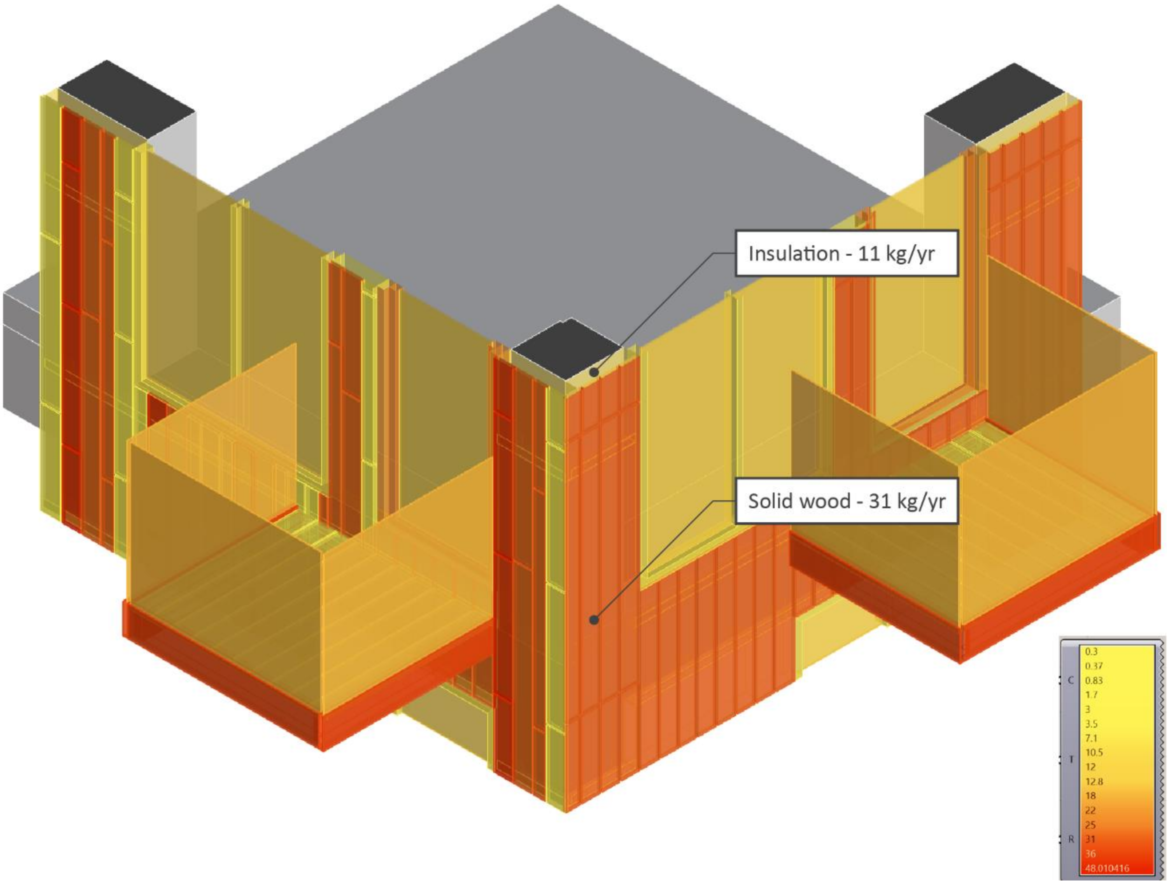


Figure 6.1.12 Embodied CO2 of used materials, dominated by the steel and wooden cladding.

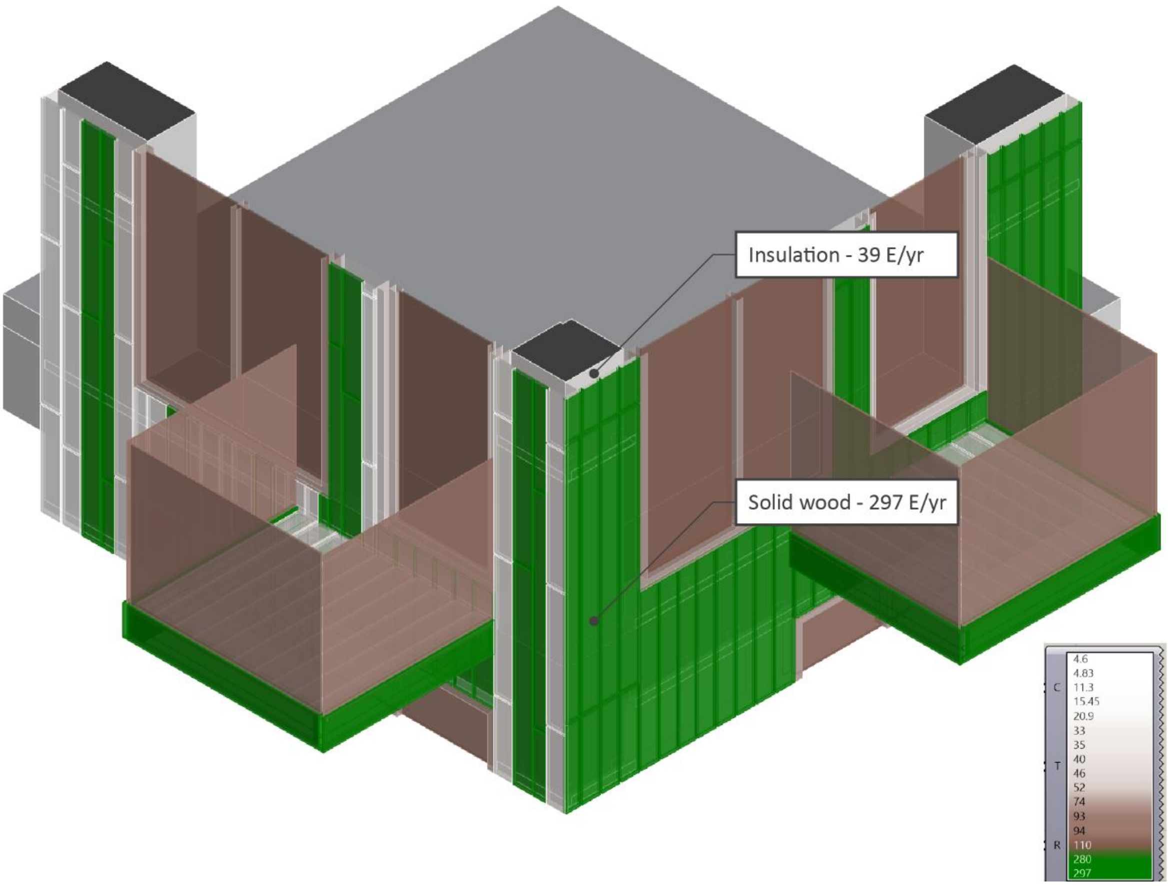


Figure 6.1.13 Cost of the material used, dominated by the amount of wood and steel.

Further, step for the analysis would be to make sure the materials that are reusable at the end of 50th year can be demounted without damage and the material that needs replacement during the use phase of the building should not damage other materials. Based on the visual assessment in **Figure 6.1.10** - **Figure 6.1.13**, it can be noticed that insulation has least expected lifetime of 26years and is 40% circular compared to wooden cladding which can last 96 years (industrial average 100 years). Wooden cladding is having still low MCI because most of it is going to be recycled at end of use phase. It also costs more because of the high share in the total mass. Embodied CO2 of the insulation is higher because of the CO2 generated in its production. Since, the mass of insulation is a small share in the total, making it more circular would not reflect in the circularity indicator. But it will however lower the environmental impacts, if it could have been sourced as secondary material.

Using the DfD aspects discussed in Chapter 2, the connections of the wooden cladding can be designed in a way that allow periodic replacement of the insulation. Secondly, materials with similar lifespan in the cladding should be aligned together to ensure easy disassembly. In a period of 50 years, the insulation must be replaced at least once. If this is not possible, then the wooden cladding must be either demolished with the insulation or the energy efficiency of the building will be compromised. In case former decision, two things should be changed the MCI variables can be changed for the wooden cladding which gives an Advanced assessment of circularity in **Table 6.1.10**. 52% circularity is achieved because 69% of the total material is recycled at EOL creating a lot more unrecoverable waste. The Embodied CO_2 and cost indicator do not change because tool does not consider the replacement cycles needed to replace the products with lower lifespan than the building.

To consider the replacement cycles, the Embodied CO_2 of the material with lower lifespan can be multiplied with the ratio of expected lifetime of the building and expected lifetime of the material. This is currently not part of the calculation method of the assessment indicators.

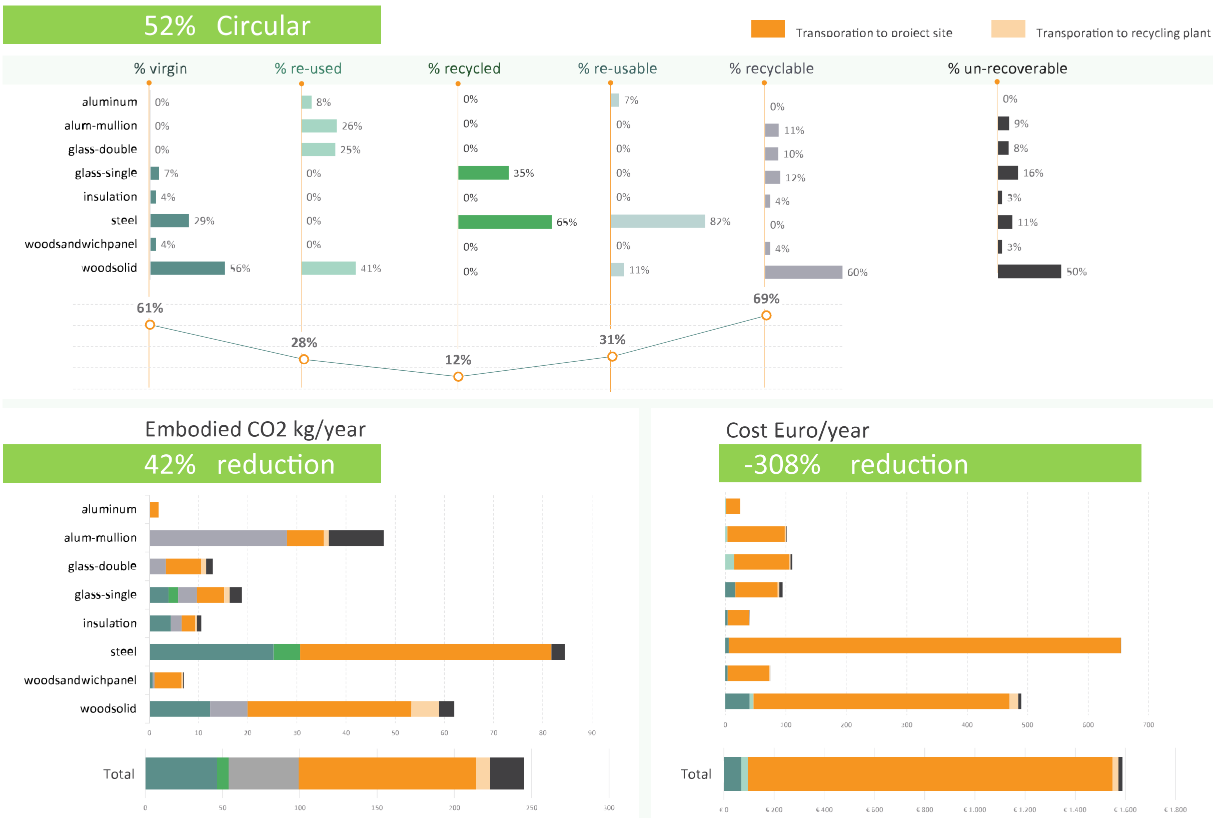


Table 6.1.10 Advanced assessment of circularity after analysing the design with DfD aspects and changing MCI variables

6.2 Assumptions

- The values of embodied CO_2 for various processes used in the database is an estimated value. Some values were taken from CES Edupak and some were assumed/altered to show results.

- A standard database is not available to estimate the cost of secondary material. Hence, the value of reused material is estimated half of the virgin equivalent.

- To estimate the CO_2 and cost reduction between a circularly and linearly flowing material. The flow of material in the later is assumed to be coming from 100% virgin and 100% of the material goes for recycling at end of use phase. Even though, most of the CDW is used as backfilling in Netherlands.

- Damage during transportation or repair work is assumed to be negligible.

- All the materials are directly reusable at the end of use phase without refurbishment or remanufacture.

6.3 Limitations

- The assessment of embodied CO_2 is based on simplified boundary condition, which exclude CO_2 generated in production, installation and maintenance. Whole building LCA must be done to analyze the benefit of using secondary material in the total environmental impacts of a building.

- The cost assessment only considers cost of material and transportation. Cost of labor for replacing components must be considered to analyze the feasibility of the business model.

- The tool does not give preference to designs that uses less material for same functional purpose.

- The limitation of doing a preliminary estimate is that, it does not consider disassembly of various elements which derives the circularity of materials.

- Subtractions in the material while designing is not considered as recyclable content in the preliminary assessment.

Conclusion

The main question addressed in this research is what information is required by architects and designers to utilize secondary material in the design process and, when and how should it be provided to them. To answer this 3-phase question, a literature study is conducted from three perspectives forming the three chapters in the report. It is found that to estimate circularity in the beginning of the design process requires information that is usually unavailable such as reusability. Reusability of building material changes when it assembled with other components of the building. To define this, DfD aspects need to be followed, which is cumbersome to do at an initial phase. By using secondary material, DfD aspects became less important because most of the material would reach EOL at the end of the use phase of the building.

Using secondary material comes with the constraint concerning geometry and technical performance. To make effective reuse of this material, information is needed at the beginning of the design. This information should include labels that help assess sustainability gains. This research aggregated all the necessary labels to make a preliminary assessment of circularity, environmental impacts, cost, technical performance and life expectancy of a material. This assessment is proposed to be actively supplied while designing. This fast pace of assessment prevents the use of material that would result in higher environmental impact when compared to linear products.

The literature review aligns EU's goal of becoming a circular economy and the right way we must practice helping this transition. It is essential to change the way we design buildings and use the material. Most of the materials used in construction have a high life expectancy. These materials can be kept in a circular flow if carefully used and reused.

The framework developed in this thesis supplies a transparent information to all stakeholders involved in the design and construction process. It constraints design freedom but also promote adaptive reuse while being aware of the challenges of using secondary material. Synergy provided between creative exploration and practical challenges allows budding innovative solutions. Bridging the existing knowledge and communication gap between Designer/engineers and owners of secondary material would yield sustainable existence of the industry.

Environmental Benefits of using secondary material in new projects should be supported by further research in the whole LCA of the building. To go with the assessment framework, a methodology should be developed to assess the amount of material used per capita in a building. This would further regulate the extraction of minimum materials and hence, less environmental impacts per capita.

This research summarizes the fallbacks of the so-called state-of-the-art practices and how assessment tools need to become designer-centric. The study radically evaluates the sustainability benefits of the current practice of designing circular buildings. The elaborated design case spreads awareness w.r.t the potential of materials banks in design processes. To accelerate circularity in built-environment, it is time to use secondary material circularly while assessing the environmental benefits of our choices.

Reflection

The following chapter describes the opinion about the success and failure of the research plan and design outcome of the thesis. It critically reflects on how collaboration with industry partners help solve a problem in real-time and being aware of challenges that cannot be predicted in the academic environment. It also paves a path for redirecting efforts in a direction that would enhance the applicability of the search for sustainable goals.

Research and methodology

The graduation topic is part of the circularity group of Architecture Engineering and Technology, Faculty of Architecture. Several research projects supporting the claims of circularity in building products come under this umbrella. Even though the final design example is portrayed in a building envelope, the tool applies to any architecture design problem, from exterior to interior and building new to renovation. Since building envelopes contributes to 30% of the total building cost, it was more interesting to intervene with it. Facades covered a lot of real performance challenges which if dealt with could lead to optimized building energy demands; this could then also contribute towards energy neutral goals of Netherlands. The topics proposed in the graduation by the faculty are interdisciplinary, and it is this approach which leads to innovative thinking and outcomes that would help the industry become more sustainable in the coming years. Hence, proposing a revolutionary approach towards how we practice architecture is necessary while we also see the advancement in computational technology in other sectors. The ideation of the studio is to break the barriers of the classical approach of architecture design and think beyond the aisles to help the environment effectively.

Research framework defined by the faculty for building technology students is broadly divided into three tiers spread across six months. The first tier is defining the main research question and objectives. The second tier required intensive literature study that would help buildup conclusions for the design process. This works perfectly when the end results in an architectural design solution. However, In this research, the focus is to design a workflow that would help architects enable the use of secondary materials easily at the early design stage. The method defined by the faculty was followed but adding a design stage in between the literature study. Hence, the approach was 5-tier. I defined first - my objective which is to make access for architects to explore options of secondary material that are available in the built environment.

Moreover, what added advantages would be of the proposal after having information from the material bank. After this stage, I did an intensive literature review on circularity goals and existing tools to measure circularity. After which, I conceptualized the U/I of the tool that I wanted to create and found the technological and database related gap of knowledge that exist to achieve the goal. This then brings me to the fourth stage of another intensive literature study for the kind of tool that exists for making a collaborative digital environment between architects and procurement. Also, custom BIM tools for assessing environmental impacts and sustainability of a building were studied. This stage ended with analyzing the skills that I possessed and what kind of workflows that can be created using the existing knowledge as well as guidance from the company on the feasibility of the proposal. The end outcome should be enough to show the workability of such a tool.

The last stage would be combining all the information from various stages and designing the workflow for a circular design project. The concept of circularity is vast with many angles from the business model, finance, applicability and industry-specific, life cycle and environmental impacts. From the structure of the report, it can be seen that one chapter is different from the other; this is because the answers did not lie in one type of discipline. It was necessary to keep an open mind and think beyond the skills and knowledge from the literature that was associated with 'circularity' directly to fill the knowledge gap.

Company collaboration

After the P1 presentation, I had realized that to achieve my research goals in time and prevent re-inventing the wheel; I need to get an industry exposure for the current state-of-the-art BIM tools and environmental assessment methods that already existed. I identified two types of collaboration that I would require for my thesis, one related to architectural BIM tools and the other from someone who maintains a material database. Using the knowledge that is already, there would make the research more acceptable and more productive after graduation. This aim is directly related to creating a social impact with the right goals and partners who have a similar intent. I applied for a position as a graduate intern at ABT for gaining experience about the methods for sustainability assessment of a building and the existing BIM tools that have been created. This provided me with case studies of an existing ABT BIM tool and also studied the circular projects within the company. In order to understand the material banks and database management techniques, I collaborated with BAM for sharing their knowledge and questions regarding circularity. It worked in benefit with both the companies as mentioned in the research plan.

While doing a thesis in collaboration with industry partners, also coming from a different culture, I learnt the difference in power distance that is very less in the Netherlands. I was initially afraid of taking hold of decisions w.r.t set up meetings, waiting for approvals etc. Also emailing different people for reviews and how accessible and appropriate was it to address them directly. It was a challenge and eye-opener that professional environment is open, you get respected for your ideas and efforts; it creates the ambience where innovation can be born. My ethics from previous experience are quite different, where the power distance is quite vast in the professional environment.

But on the contrary, the educational institution that I come from is quite open with comments and feedback. I could knock at the door and ask anything. We never wrote an email to our faculty for appointments. The speed of feedback was quite fast there, and this posed an ethical challenge that I could not address the people directly at times at the faculty.

Nevertheless, this posed as a confused approach because I could address some people at a higher level of responsibility directly, but some constrained to email only. I later decided to address nearby people directly to make my research feedback faster and took it positively if they did not like it. The whole experience in two years taught me that I need to take responsibility for my project and success and extract fruitful information, from whomever and however.

Societal impact and applicability

The broader objective of the research project is to preserve our natural environment, which is getting depleted day by day due to afforestation, mining and burning fossil fuels. All this is leading to global warming and rising sea level. The climate action promotes synergy between different stakeholders to become more sustainable and finance institutions and projects related to Circular economy. The Netherlands itself produced 12.2 tonnes of greenhouse gases per capita in 2016. The graduation project is directed towards re-using the full potential of any made product and keeping it in a loop in an informed way as long as possible. By doing this, we are already further in becoming sustainable. These efforts can be visualized on a large scale in Circularity indicators set by the European Commission, specifically Circular Material Use rate, which indicates the contribution of recycled material in total material demands.

Due to industry collaboration, it made sure that the goals are achievable and not superficial. Also, it optimized the time spent on specific internal questions which could only be answered by experts in the field. To achieve the Netherlands goal of 100% circular, we need to accelerate the use of secondary material. It was a simple goal with much inter-disciplinary research. For example, I never worked in the construction sector and did not know how their internal organization is set up. Both the companies are actively working on the circularity goals of Netherlands and making a change in the way we administer our resources.

The impact of the research is directly on how we procure circular material keeping in mind the design freedom. If applied in the industry, it would accelerate the use of secondary material in all architectural projects as well as revolutionize the way we design on a blank canvas. In order to make this widely useable, a stakeholder powerful as BAM is capable of implementing this proposal and also fit with BAM's goal to be a circular company. The tool becomes a guideline for the architects to procure architectural components at the beginning of the design and use it as the Lego bricks for building. It directly informs architects about the circularity and environmental impacts of the chosen secondary material and compared with a similar virgin source. It creates social awareness within the design process itself and creative procurement while designing. Hence, procurement becomes an essential part of a continuous design process.

The cultural change that can be expected is how we retrieve materials from the existing building. The documentation process becomes more critical because gradually, the discarded components will have more value in creative hands. At present, the demolition activities only take into account the mass retrieved from buildings. This gives less or no information about the geometrical properties of these components, which is essential for it to be re-used in another design. Adding the parameters mentioned in the research will add value to the product. In the changing economy, secondary material is going to become more valuable because of the rising expense of virgin materials. Hence, use, maintenance, refurbishment and resale of a product become a primary management process for any product. To accelerate this process and keep the material in an economic loop, it becomes essential to have a standard set of labels for everything. Otherwise, it is a loss for the manufacture and of course affect the environment adversely.

In the coming time when CO2 taxes are going to escalate on raw material, re-using existing raw-material and products will no longer be goodwill, it will no longer be economical to use virgin material for various products. Hence, it is better to be prepared to use secondary materials efficiently and effectively.

Outcome

The outcome of the research can be seen in two parts. Firstly, the literature studies that were designed to address the state-of-the-art from various disciplines. This showcased the abundance of potential interventions to achieve sustainable goals in the built environment. The literature can be used as a starting point for other research projects. It also shows how to link different research to benefit another different study. The scientific aspect of the research is to discover the potential of relative research that would not be recognized otherwise. This was done by identifying the concepts that were indirectly related to circularity but may not have been derived from the concept initially. The final tool depicts the importance and need of a Circular Building Platform that does more than a stagnant library of materials. Both the company collaborations also agreed with this goal. It was intended to come up with a solution that could be immediately implemented in the industry and also identifying the potential of an advanced custom tool to minimize the steps of workflow further. The thesis can be used as a proof of concept for custom BIM application/plugin that would facilitate all the steps in a single interface to procure and assess circular products.

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Appendices

Appendix 1 Design for Disassembly aspects defined by (Durmisevic, 2006)

Appendix 2 Expert Interviews

Appendix 3 Database structure

Appendix 4 Madaster Inventory of source files

Appendix 5 Visual Scripts

Appendix 1 Design for Disassembly aspects defined by (Durmisevic, 2006)

Aspect	Criterion	Code	Description	grading
FD FUNCTIONAL DECOMPOSITION	functional separation	fs 01	separation of functions	1
		fs 02	integration of functions with same lc* into one element	0,6
		fs 03	integration of functions with different lc* into one element	0,1
			fs = [fs1+ fs2 + ….fs(n)] / n	
	functional dependence	fdp 01	modular zoning	1
		fdp 02	Planed interpenetrating for different solutions (overcapacity)	0,8
		fdp 03	Planed interpenetrating for one solution	0,4
		fdp 04	Unplanned interpenetrating	0,2
		fdp 05	total dependence	0,1
			fdp = [fdp1+ fdp2 + ….fdp(n)] / n	
			FD = fuzzy calculation based on "fs" and "fdp" and their weighting factors	
SY SYSTEMATISATION	structure and material levels	st 01	components	1
		st 02	elements / components	0,8
		st 03	elements	0,6
		st 04	material / element / component	0,4
		st 05	material / element	0,2
		st 06	material	0,1
			st = [st1+ st2 + ….st(n)] / n	
	clustering	c 01	clustering according to the functionality	1
		c 02	clustering according to the material life cycle	0,6
		c 03	clustering for fast assembly	0,3
		c 04	no clustering	0,1
			c = [st1+ st2 + ….st(n)] / n	
			SY: = fuzzy calculation based on "st" and "c" and their weighting factors	
BE BASE ELEMENT	base element specification	b 01	base element- intermediary between systems /components	1
		b 02	base element- on two levels	0,6
		b 03	element with two functions (be. and one building function)	0,4
		b 04	no base element	0,1
			b = [b1+ b2 + ….b(n)] / n	
			BE = fuzzy calculation based on "b" and its weighting factor	
LCC LIFE CYCLE CO-ORDINATION	use life cycle/ coordination (1)- assembled first (2)- second	ulc 01	long LC (1) / long LC (2) or short LC(1) / short LC(2)	1
		ulc 02	long LC(1) / short LC(2)	0,8
		ulc 03	medium LC (1) / long LC (2)	0,6
		ulc 04	short LC (1) / medium (2)	0,3
		ulc 05	short (1) / long LC (2)	0,1
			ulc = [ulc1+ulc2 + ….ulc(n)] / n	
	technical life cycle/ coordination	tlc 01	long LC (1) / long LC (2) or short (1) / short (2) or long (1) short (2)	1
		tlc 02	medium LC (1) / long LC (2)	0,5
		tlc 03	short LC (1) / medium LC (2)	0,3
		tlc 04	short LC (1) / long LC (2)	0,1
			tlc = [tlc1+ tlc2 + ….tlc(n)] / n	

				grading
LCC LIFECYCLE CO-ORDINATION	lifecycle of components and alelents in relation to the size (1)- assembled first	s 01	small element (1) / short LC or medium component (1) / short LC	1
		s 02	big component (1) / long L.C.	1
		s 03	big (small) element (1) / long LC	0,8
		s 04	big component (1) / short LC	0,4
		s 05	material (1) / short L.C.	0,2
		s 06	big element / short L.C. or material / short life cycle	0,1

s = [s1+ s2 + ….s(n)] / n

LCC = fuzzy calculation based on "ulc","tlc" and "s" and their weighting factors

RP RELATIONAL PATTERN	position of relations in relational diagram	r 01	vertical	1
		r 02	horizontal in lower zone of the diagram	0,6
		r 03	horizontal between upper and lower zone of the diagram	0,4
		r 04	horizontal in upper zone	0,1

r = [r1+ r2 + ….r(n)] / n

RP = fuzzy calculation based on "r" and its weighting factor

A ASSEMBLY	assembly direction based on assembly type	ad 01	parallel - open assembly	1
		ad 02	stuck assembly	0,6
		ad 03	base el.in stuck assembly	0,4
		ad 04	sequential seq.base el	0,1
			ad= [ad1+ ad2 + ….ad(n)] / n	
	assembly sequences regarding material levels (1)- assembled first (2)- second	as 01	component (1) / component (2)	1
		as 02	component (1) / element (2)	0,8
		as 03	element (1) / component (2)	0,6
		as 04	element (1) / element (2)	0,5
		as 05	material (1) / component (2)	0,3
		as 06	component (1)/material (2)	0,2
		as 07	material (1) / material (2)	0,1

as= [as1+ as2 + ….as(n)] / n

A = fuzzy calculation based on "ad" and "as" and their weighting factors

G GEOMETRY	geometry of product edge	gp 01	open linear	1
		gp 02	symmetrical overlapping	0,8
		gp 03	overlapping on one side	0,7
		gp 04	unsymmetrical overlapping	0,4
		gp 05	insert on one sides	0,2
		gp 06	insert on two sides	0,1
			gp= [gp1+ gp2 + ….gp(n)] / n	
	standardisation of product edge	spe 01	pre-made geometry	1
		spe 02	half standardised geometry	0,5
		spe 03	geometry made on the construction site	0,1

spe= [spe1+ spe2 + ….spe(n)] / n

G = fuzzy calculation based on "gp" and "spe" and their weighting factors

				grading
C CONNECTIONS	type of connection	tc 01	accessory external connection or connection system	1
		tc 02	direct connection with additional fixing devices	0,8
		tc 03	direct integral connection with inserts (pin)	0,6
		tc 04	direct integral connection	0,5
		tc 05	accessory internal connection	0,4
		tc 06	filled soft chemical connection	0,2
		tc 07	filled hard chemical connection	0,1
		tc 08	direct chemical connection	0,1
			tc= [tc1+ tc2 + ….tc(n)] / n	
	accessibility to fixings and intermediary	af 01	accessible	1
		af 02	accessible with additional operation which causes no damage	0,8
		af 03	accessible with additional operation / causes reparable damage	0,6
		af 04	accessible with additional operation/causes partly reparable damage	0,4
		af 05	not accessible - total damage of bought elements	0,1
			af= [af1+ af2 + ….af(n)] / n	
	tolerance	t 01	high tolerance	1
		t 02	minimum tolerance	0,5
		t 03	no tolerance	0,1
			t= [t1+ t2 + ….t(n)] / n	
	morphology of joint	mc 01	knot (3D connections)	1
		mc 02	point	0,8
		mc 03	linear (1D connections)	0,6
		mc 04	service (2D connection)	0,1

mc= [mc1+ mc2 + ….mc(n)] / n

C = fuzzy calculation based on "tc","af","t" and "mc" and their weighting factors

Appendix 2 Expert Interviews

For in-depth knowledge and technical consultation ABT company was collaborated with for state-of-the-art building information modelling. Several meetings were scheduled with experts from BIM, plugin development, sustainability experts. Marcel Tabak member of Architecture and Sustainability group at ABT introduced me to various possible cases and people that would be essential to meet with respect to the topic. After the meeting with Sandra from ABT, she explained the potential challenges like level of detail, existing material banks, IFC classes, NL/sfb codes etc. These were later in cooperated with the list of parameters for the smart material bank proposal. Jeroen van Kuik is BIM modular with 20 years of experience. After meeting with him, he introduced me to the MIM ABT tool for calculating environmental impact of new structural components. It is a plugin for Autodesk revit software and made in-house. This will become one of the case studies at a later stage. Emergis project from ABT focuses on the re-use of a wooden structure from a demountable building. The wooden components were re-designed to form the structural concept of the new building. This is also included in the case study example of material re-use, focus on the challenges faced during the process is focused.

Marcel Tabak, ABT

Q: What are the current trends in circularly built project?

A: The demand of circularity is increasing every year in our tenders. Clients want to have higher circularity value in their project. That means more products should be re-usable after the use-phase. We at ABT are trying to build the knowledge of circular construction and how we can be prepared for this challenge.

For example, our office in Delft is designed in a way that we could disassemble it and re-use its component somewhere else. We are trying to understand how these building components be reused to expand our Gronigen office. We had students in past (Wouter Dusseldorp) that developed a assessment criteria to measure the circularity of a building which could also be helpful for you.

Q: Do you use any inhouse tool to measure the circularity of your project?

A: No, we do not have currently a matrix that could estimate this. For us it is more important to know what material is usable and its specifications to explore its potential in a new design. For example, in our project Emergis-Ihtaka we re-used structural timber from the disassembled office of Rijkswaterstaat inTerneuzen. GertJan Rozemeijer was the project manager for that and he can tell you in detail how we used the wooden beams to propose a new structural system.

Q: Are there any current projects that are being designed using circular principles?

A: In our project Unnik Building, Utrecht, we need to refurbish the façade of the building and are estimating how much material from the façade of the building can be re-used. For this we have listed down the criteria that we want to use (shown below). But we are still researching on how we can estimate circularity to a single value. Eveline Gootzen can tell you more about the project.

Bestaande situatie **Inspecteren**	**Technische kwaliteit**	Conditiescore conform NEN 2767	1 - 6
		Maatvastheid	1 - 3
		Negatief effect materiaal op gezondheid	ja/nee
	De-/ remontage	Arbeidsintensiteit (de)montage	1 - 3
		Kans op beschadiging bij demontage	1 - 3
		Kwetsbaarheid bij demontage, vervoer en opslag	1 - 3
+			
Toekomstige situatie **Controleren / Analyseren**	**Potentieel hergebruik**	Nieuwbouw zonder bewerking (BB2012)	ja/nee
		Nieuwbouw met bewerking (BB2012)	ja/nee
		Bestaande bouw zonder bewerking (BB2012)	ja/nee
		Bestaande bouw met bewerking (BB2012)	ja/nee
		Andere functie	1 - 3
		Recycle materiaal	1 - 3
		Downcycle materiaal	1 - 3
	Risico's	Mogelijkheid voor opslag	1 - 3
		Garantie	1 - 3
+			
Waarderen	**Potentiële waarde**	Potentiële milieuwinst	1 - 3
		Economische waarde	1 - 3
		Esthetische waarde	1 - 3
		Bouwhistorische waarde	1 - 3
=			
Circulariteitswaarde			

Q: How do we take into account environmental impacts of materials at ABT and what database do we use for it?

A: We calculate the CO_2 impact by studying the specifications from the design model and finding the data from Nationale Milieudatabase. It contains the building material that are supplied within the Netherlands, although not all components have information. We have developed an environmental assessment tool called ABT MIM tool to measure the embodied CO_2 of structural components made of concrete or wood. It is a Revit Addin and collects environmental data from an excel sheet. We are hoping to extend its functionality to architectural material as well in future.

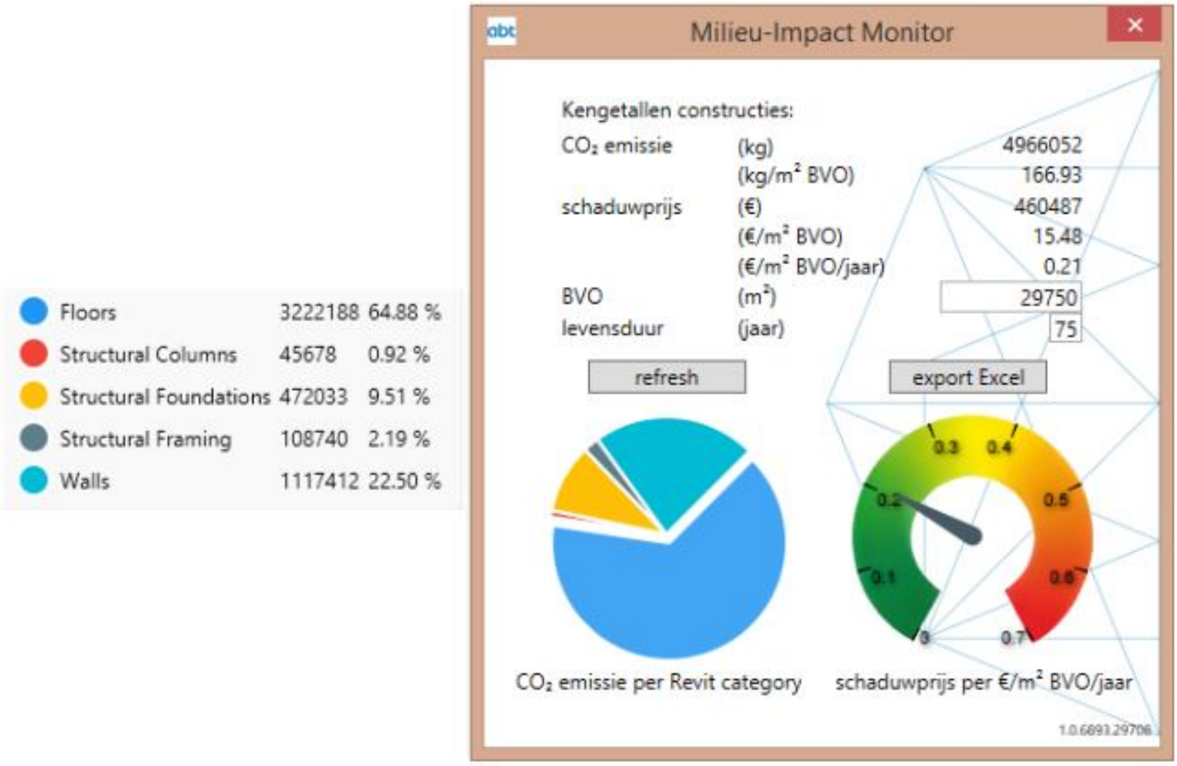
Q: How was the MIM tool developed and how is it used?

A: It was made using Revit developer tools and C# coding language. Michiel can explain you better about the working and Jeroen van Kuik can explain how we use it in our projects.

Jeroen van Kuijk

Q: How does the MIM tool work?

A: We use this tool to estimate the CO_2 footprint and shadow price of concrete and wooden structural elements. For this we have used the values from Nationale Milieudatabase. The data processing is in real time 3D environment and hence it makes it unique. Hence, when you make changes to the design you can immediately check the assessment. The shadow price is calculated both in absolute terms and per year (as shown below). The results can be used to determine the MPG calculations, BREEAM certification and GPR calculation.



Jaco Prins, BAM

Q: How is material database created currently at BAM?

A: We do not have an aggregated database of materials at BAM but in the Circl Pavilion we made sure that all our suppliers must submit a 3D model of the installations and building components. It was difficult to convince the client how important it was to document the building components in order enable its re-use in future. Documenting this information also came with price which was not a problem in this project.

Q: What was the procurement process like in the Circl project?

I did not participate directly in the procurement but we discussed everything around table with other consultants, from façade, structural and architect. New horizon provided part of the material such as the basement partition walls and part of electrical installations. The procurement process is generally carried out at the end of the architecture design and we get the requirements and specifications from the BIM model. In case of Circl the procurement that had a huge impact on the aesthetic was done by the architect while consulting with all other parties involved. The transparency in procurement made it easier for the contractors as well to install these and this was made even easier by having the digital identity of the materials beforehand. We did not have any clashes at the construction site because everything was discussed unanimously.

Q: How do you think an architectural database can be created? Which one is suitable MySQL or RDMS?

For Architectural material database MySQL or SQL database is enough as we do not need to understand cross relationships between various components that are not directly connected to each other. There are at least 400 types architectural components including MEP and other materials which an SQL database can easily handle. (RDMS is more suitable for theft detection or e-marketing)

David Vos, BAM

Q: How do we ensure circular procurement at BAM?

A: We research on various platforms what kind of material is available and is useful in design. We are increasingly getting requests from client that they want to apply circular principles in their building. And now we are trying to make BAM a 100% circular company. For that we are developing a Circular Building platform (CBP) where we can act as an 'Ebay' of materials. Currently we donot have any material in our database and we are exploring what kind of labels should we include in it.

Q: How does the procurement look like in circular projects?

A: We have designed a building without looking into secondary materials. But now the demand from the client has come that it should be a circular building and now we are trying to find products that fit the best. Your tool enables to compare the database on sizes and I think it is very relevant to the current practice. The design phases that you have shown, covers the procurement requirement and the assessment criteria provided enough information in making a decision.

Q: What are the key components that you look for procurement?

A: In the beginning, the size, material, geometry and quantity are the most essential for considering in the design of a new building or a refurbishment project. You have covered all these aspects in your proposal and really adds value for architects. This becomes like designing with 'lego bricks'.

Appendix 3 Database structure

Material info

Material	Density	Cost Euro/kg	Virgin CO2kg/kg	Recycling CO2/kg	Recycle efficiency	Landfill CO2/kg	Transport CO2/kg per km	Age	Thermal conductivity	Acoustic velocity (m/s)	Uvalue	Fire rating	Date of manufacture	Date of today	Expected Industrial average life	recycled content	energy through combustion (J/kg)	Location	CO2 generated through combustion (kg/kg)	Cost of transport / m3 km (Euro)
					Ef	Cl	Ct								Lav					
woodboard	900	0,4	1,05	1,05	0,8	2,1	0,026	4	0,35	2580	0	4	41824	43649	25	0,5	0,6	Gronigen	1	0,33
woodsolid	890	2,27	0,7	0,7	0,8	1,4	0,026	4	0,35	2580	0	4	41824	43649	100	0,5	0,6	amsterdam	1	0,33
aluminum	2700	1,8	14,6	14,6	0,8	29,2	0,026	4	201	5130	0	4	41824	43649	70	0,5	0,6	zwolle	1	0,33
alum-mullior	1350	1,8	14,6	14,6	0,8	29,2	0,026	4	201	5130	0	4	41824	43649	70	0,3	0,6	amsterdam	1	0,33
steel	7800	0,6	2,75	2,75	0,8	5,5	0,026	4	54	5240	0	4	41824	43649	100	0,5	0,6	hengelo	1	0,33
woodsandwi	250	2,6	0,5	0,5	0,8	1	0,026	4	0,03	2080	0	4	41824	43649	30	0,5	0,6	hengelo	1	0,33
alumsandwic	50	2,6	0,2	0,2	0,8	0,4	0,026	4	0,03	2080	0	4	41824	43649	30	0,5	0,6	arnhem	1	0,33
glass-single	2350	7,85	1,83	1,83	0,8	3,66	0,026	4	1,1	5350	1,5	4	41824	43649	50	0,5	0,6	amsterdam	1	0,33
glass-double	4600	7,85	1,83	1,83	0,8	3,66	0,026	4	1,1	5350	2,5	4	41824	43649	50	0,5	0,6	hague	1	0,33
glass-tripple	6900	7,85	1,83	1,83	0,8	3,66	0,026	4	1,1	5350	3,5	4	41824	43649	50	0,5	0,6	amsterdam	1	0,33
brick	2070	1,4	0,23	0,23	0,8	0,46	0,026	4	0,8	5380	0	4	41824	43649	70	0,5	0,6	amsterdam	1	0,33
insulation	32	2,6	3,1	3,1	0,8	6,2	0,026	4	0,03	2080	0	4	41824	43649	30	0,5	0,6	arnhem	1	0,33
acp	50	1.81	0,2	0,2	0,8	0,4	0,026	4	0,03	5130	0	4	41824	43649	70	0,5	0,6	zwolle	1	0,33
concrete	2000	0,05	0,1	0,1	0,8	0,2	0,026	4	0,7	1220	0	4	41824	43649	100	0,5	0,6	eindhoven	1	0,33
reinforcedco	2000	0,05	0,1	0,1	0,4	0,2	0,026	4	0,7	1220	0	4	41824	43649	100	0,5	0,6	amsterdam	1	0,33
stone	2850	0,8	0,1	0,1	0,8	0,2	0,026	4	6	5040	0	4	41824	43649	70	0,5	0,6	hengelo	1	0,33
pvc	1310	2.68	0,1	0,1	0,8	0,2	0,026	4	0,03	1060	0	4	41824	43649	70	0,5	0,6	amsterdam	1	0,33
copper	8950	5	3,6	3,6	0,8	7,2	0,026	4	170	3500	0	4	41824	43649	70	0,5	0,6	hague	1	0,33
bamboo	800	1,7	0,83	0,83	0,8	1,66	0,026	4	0,18	5550	0	4	41824	43649	70	0,5	0,6	amsterdam	1	0,33

Distance Calc

Product locations	From Gronigen	From Amsterdam	From Hague	From Zwolle	From Hengelo	From Arnhem	From Eindhoven	distance	project site
gronigen	0	10	100	60	40	80	200	100	hague
amsterdam	10	0	50	50	100	60	100	50	hague
hague	150	50	0	60	150	75	100	0	hague
zwolle	50	40	65	0	30	30	125	65	hague
hengelo	40	60	150	30	0	40	125	150	hague
arnhem	80	60	75	30	30	0	65	75	hague
eindhoven	200	100	100	125	125	65	0	100	hague

Column1	Column2
project site	hague
Use life yr	50

Life cycle management

lookup code	product code	lifecycle	Material	Total Weight (kg)	Virgin feedstock (%)	Weight of Virgin mass (kg)	Reused feedstock (%)	Weight of Re-used content (kg)	Recycled feddstock (%)	Weight of Recycled content(kg)	Recycled efficiency	Waste of recycled content(kg)	Recycling potential
0a2	0a	2	reinforcedconcrete	33600	0	0	1	33600	0	0	0,4	0	0
1a2	1a	2	brick	2691	0	0	1	2691	0	0	0,8	0	1
2a2	2a	2	insulation	83,2	0	0	1	83,2	0	0	0,8	0	1
3a2	3a	2	glass-single	705	0	0	1	705	0	0	0,8	0	1
3b2	3b	2	alum-mullion	810	0	0	1	810	0	0	0,8	0	1
4a2	4a	2	stone	10260	0	0	1	10260	0	0	0,8	0	1
					1								0
					1								0
5a1	5a	1	glass-single	211,5	0,5	105,75	0	0	0,5	105,75	0,8	26,4375	1
6a1	6a	1	steel	280,8	0,7	196,56	0	0	0,3	84,24	0,8	21,06	0
7a1	7a	1	steel	280,8	0,7	196,56	0	0	0,3	84,24	0,8	21,06	0
8a1	8a	1	steel	93,6	0,7	65,52	0	0	0,3	28,08	0,8	7,02	0
9a1	9a	1	woodsolid	89	1	89	0	0	0	0	0,8	0	0
					1								0
					1								0
10a1	10a	1	woodsolid	106,8	0	0	1	106,8	0	0	0,8	0	1
11a1	11a	1	alum-mullion	99,9	0	0	1	99,9	0	0	0,8	0	1
11b1	11b	1	alum-mullion	91,8	0	0	1	91,8	0	0	0,8	0	1
11c1	11c	1	glass-double	184	0	0	1	184	0	0	0,8	0	1
12a1	12a	1	woodsandwichpanel	30	1	30	0	0	0	0	0,8	0	1
13a1	13a	1	woodsandwichpanel	40	1	40	0	0	0	0	0,8	0	1
					1								0
					1								0
14a2	14a	2	aluminum	9,072	0	0	1	9,072	0	0	0,8	0	0
15a2	15a	2	aluminum	10,8	0	0	1	10,8	0	0	0,8	0	0
16a2	16a	2	aluminum	34,56	0	0	1	34,56	0	0	0,8	0	0
17a1	17a	1	insulation	70,4	1	70,4	0	0	0	0	0,8	0	1
18a1	18a	1	woodsolid	791,21	1	791,21	0	0	0	0	0,8	0	0
19a1	19a	1	woodsolid	32,04	0	0	1	32,04	0	0	0,8	0	0
20a1	20a	1	woodsolid	99,68	0	0	1	99,68	0	0	0,8	0	0
21a1	21a	1	woodsolid	56,96	0	0	1	56,96	0	0	0,8	0	0

lookup code	Weight of recyclable content (kg)	Recycling efficiency	Waste of recyclable content (kg)	Reusable potential (%)	Weight of re-usable content (kg)	Un-usable waste (%)	Weight of Unrecoverable waste (kg)	Linear Flow Index	Expected Life-time (yr)	Industry Average Life-time (yr)	Utility factor	MCI	MCI * W	Location
0a2	0	0,4	0	1	33600	0	0	0	100	100	0,9	1,00	33600,00	hague
1a2	2691	0,8	538,2	0	0	0	269,1	0,05263158	25	70	2,52	0,87	2334,09	hague
2a2	83,2	0,8	16,64	0	0	0	8,32	0,05263158	0,01	30	2700	0,00	0,00	hague
3a2	705	0,8	141	0	0	0	70,5	0,05263158	0,01	50	4500	0,00	0,00	hague
3b2	810	0,8	162	0	0	0	81	0,05263158	50	70	1,26	0,93	756,28	hague
4a2	10260	0,8	2052	0	0	0	1026	0,05263158	0,01	70	6300	0,00	0,00	hague
				1										
				1										
5a1	211,5	0,8	42,3	0	0	0	34,36875	0,33757962	50	50	0,9	0,70	147,24	amsterdam
6a1	0	0,8	0	1	280,8	0	10,53	0,36196319	100	100	0,9	0,67	189,32	hengelo
7a1	0	0,8	0	1	280,8	0	10,53	0,36196319	100	100	0,9	0,67	189,32	hengelo
8a1	0	0,8	0	1	93,6	0	3,51	0,36196319	100	100	0,9	0,67	63,11	hengelo
9a1	0	0,8	0	1	89	0	0	0,5	100	100	0,9	0,55	48,95	amsterdam
				1										
				1										
10a1	106,8	0,8	21,36	0	0	0	10,68	0,05263158	30	100	3	0,84	89,94	eindhoven
11a1	99,9	0,8	19,98	0	0	0	9,99	0,05263158	50	70	1,26	0,93	93,28	arnhem
11b1	91,8	0,8	18,36	0	0	0	9,18	0,05263158	50	70	1,26	0,93	85,71	arnhem
11c1	184	0,8	36,8	0	0	0	18,4	0,05263158	46	50	0,97826087	0,95	174,53	arnhem
12a1	30	0,8	6	0	0	0	3	0,57894737	30	30	0,9	0,48	14,37	hengelo
13a1	40	0,8	8	0	0	0	4	0,57894737	30	30	0,9	0,48	19,16	hengelo
				1										
				1										
14a2	0	0,8	0	1	9,072	0	0	0	66	70	0,95454545	1,00	9,07	zwolle
15a2	0	0,8	0	1	10,8	0	0	0	66	70	0,95454545	1,00	10,80	zwolle
16a2	0	0,8	0	1	34,56	0	0	0	66	70	0,95454545	1,00	34,56	zwolle
17a1	70,4	0,8	14,08	0	0	0	7,04	0,57894737	26	30	1,03846154	0,40	28,07	arnhem
18a1	0	0,8	0	1	791,21	0	0	0,5	96	100	0,9375	0,53	420,33	amsterdam
19a1	0	0,8	0	1	32,04	0	0	0	96	100	0,9375	1,00	32,04	amsterdam
20a1	0	0,8	0	1	99,68	0	0	0	96	100	0,9375	1,00	99,68	amsterdam
21a1	0	0,8	0	1	56,96	0	0	0	96	100	0,9375	1,00	56,96	amsterdam

lookup code	Distance from project site	Energy through combustion	CO2 due to virgin mass (kg)	CO2 due to recycled content (kg)	CO2 due to recyclable content (kg)	CO2 due to distance from project site (kg)	CO2 due to unrecoverable waste (kg)	Cost due to transport (Euro)	CO2 of transport to recycling plant (kg)	CO2 of maintainance and installation	Embodied CO2 (kg/yr)
0a2	0	0,60	0,00	0,00	0,00	0,00	0,00	0,00	174,72	0,75	0,00
1a2	0	0,60	0,00	0,00	6,19	0,00	2,48	0,00	13,99	0,49	22,66
2a2	0	0,60	0,00	0,00	2,58	0,00	1,03	0,00	0,43	0,69	4,04
3a2	0	0,60	0,00	0,00	12,90	0,00	5,16	0,00	3,67	0,81	21,73
3b2	0	0,60	0,00	0,00	118,26	0,00	47,30	0,00	4,21	0,50	169,78
4a2	0	0,60	0,00	0,00	10,26	0,00	4,10	0,00	53,35	0,84	67,72
										0,03	
										0,59	
5a1	50	0,60	3,87	1,94	3,87	5,50	2,52	69,80	1,10	0,65	18,79
6a1	150	0,60	10,81	2,32	0,00	21,90	1,16	277,99	1,46	0,02	36,19
7a1	150	0,60	10,81	2,32		21,90	1,16	277,99	1,46	0,76	36,19
8a1	150	0,60	3,60	0,77	0,00	7,30	0,39	92,66	0,49	0,55	12,06
9a1	50	0,60	1,25	0,00	0,00	2,31	0,00	29,37	0,46	0,98	3,56
										0,75	
										0,55	
10a1	100	0,60	0,00	0,00	0,75	5,55	0,30	70,49	0,56	0,01	7,16
11a1	75	0,60	0,00	0,00	14,59	3,90	5,83	49,45	0,52	0,60	24,84
11b1	75	0,60	0,00	0,00	13,40	3,58	5,36	45,44	0,48	0,73	22,82
11c1	75	0,60	0,00	0,00	3,37	7,18	1,35	91,08	0,96	0,25	12,85
12a1	150	0,60	0,30	0,00	0,15	2,34	0,06	29,70	0,16	0,39	3,01
13a1	150	0,60	0,40	0,00	0,20	3,12	0,08	39,60	0,21	0,63	4,01
14a2	65		0,00	0,00	0,00	0,31	0,00	3,89	0,05		0,31
15a2	65		0,00	0,00	0,00	0,37	0,00	4,63	0,06		0,37
16a2	65		0,00	0,00	0,00	1,17	0,00	14,83	0,18		1,17
17a1	75		4,36	0,00	2,18	2,75	0,87	34,85	0,37		10,53
18a1	50		11,08	0,00	0,00	20,57	0,00	261,10	4,11		31,65
19a1	50		0,00	0,00	0,00	0,83	0,00	10,57	0,17		0,83
20a1	50		0,00	0,00	0,00	2,59	0,00	32,89	0,52		2,59
21a1	50		0,00	0,00	0,00	1,48	0,00	18,80	0,30		1,48

lookup code	CO2 of a linear equivalent (kg)	CO2 reduction	Cost of virgin content (Euro)	Cost of reused content (Euro)	Cost of transport to the recycling plant	Cost of transportation of recyclable content (Euro/yr)	Cost of Landfill (Euro/yr)	Cost/yr (Euro)	Cost of linear equivalent (Euro)	Cost reduction
0a2	1229,76	100%	0,00	16,80	2217,60	0,00	0,00	16,8	3259,2	99%
1a2	107,48	79%	0,00	37,67	177,61	68,31	14,49	37,674	333,684	89%
2a2	13,48	70%	0,00	2,16	5,49	2,11	0,83	2,1632	13,5616	84%
3a2	71,02	69%	0,00	55,34	46,53	17,90	21,29	55,3425	178,365	69%
3b2	474,66	64%	0,00	14,58	53,46	0,00	0,00	14,58	106,92	86%
4a2	892,62	92%	0,00	82,08	677,16	260,45	31,57	82,08	1764,72	95%
5a1	21,31	12%	16,60	0,00	13,96	0,00	3,99	86,39775	53,5095	-61%
6a1	52,71	31%	2,36	0,00	18,53	0,00	0,24	280,35072	47,1744	-494%
7a1	52,71	31%	2,36	0,00	18,53	0,00	0,24	280,35072	47,1744	-494%
8a1	17,57	31%	0,79	0,00	6,18	0,00	0,08	93,45024	15,7248	-494%
9a1	5,14	31%	4,04	0,00	5,87	0,00	0,00	33,4106	12,5846	-165%
10a1	6,17	-16%	0,00	2,42	7,05	0,00	0,00	72,91236	15,10152	-383%
11a1	58,54	58%	0,00	1,80	6,59	0,00	0,00	51,2487	13,1868	-289%
11b1	53,79	58%	0,00	1,65	6,06	0,00	0,00	47,0934	12,1176	-289%
11c1	13,75	7%	0,00	14,44	12,14	0,00	0,00	105,524	41,032	-157%
12a1	3,07	2%	1,56	0,00	1,98	0,00	0,00	31,26	6,24	-401%
13a1	4,09	2%	2,08	0,00	2,64	0,00	0,00	41,68	8,32	-401%
14a2	5,39	94%	0,00	0,16	0,60	0,00	0,00	4,055184	1,279152	-217%
15a2	6,41	94%	0,00	0,19	0,71	0,00	0,00	4,8276	1,5228	-217%
16a2	20,52	94%	0,00	0,62	2,28	0,00	0,00	15,44832	4,87296	-217%
17a1	11,40	8%	3,66	0,00	4,65	1,79	0,70	38,5088	11,4752	-236%
18a1	45,73	31%	35,92	0,00	52,22	0,00	0,00	297,020234	111,877094	-165%
19a1	1,85	55%	0,00	0,73	2,11	0,00	0,00	11,300508	4,530456	-149%
20a1	5,76	55%	0,00	2,26	6,58	0,00	0,00	35,157136	14,094752	-149%
21a1	3,29	55%	0,00	1,29	3,76	0,00	0,00	20,089792	8,054144	-149%

Design dataset

Product code	NL/Sfb	Material	Life cycle level	U-value (W/m² K)	Thermal conductivity W/m °C	Acoustic velocity (m/s)	Density (kg/m3)	Volume (m3)	Weight (Kg)	Quantity	Length	Depth	Height
									M				
0a	28,2	reinforcedconcrete	2	0	0,7	1220	2000	16,8	33600	1	0	0	0
1a	28,2	brick	2	0	0,8	5380	2070	1,3	2691	1	0	0	0
2a	41,1	insulation	2	0	0,03	2080	32	2,6	83,2	1	0	0	0
3a	31,1	glass-single	2	1,5	1,1	5350	2350	0,3	705	1	0	0	0
3b	31.1	alum-mullion	2	0	201	5130	1350	0,6	810	1	0	0	0
4a	43.1	stone	2	0	6	5040	2850	3,6	10260	1	0	0	0
5a	31.1	glass-single	1	1,5	1,1	5350	2350	0,015	211,5	6	1500	8	1200
6a	31.2	steel	1	0	54	5240	7800	0,006	280,8	6	1580	40	240
7a	31.3	steel	1	0	54	5240	7800	0,006	280,8	6	1500	80	200
8a	31.4	steel	1	0	54	5240	7800	0,003	93,6	4	1420	50	100
9a	31.5	woodsolid	1	0	0,35	2580	890	0,005	89	20	0	0	0
10a	31,6	woodsolid	1	0	0,35	2580	890	0,06	106,8	2	1600	100	3000
11a	31.6	alum-mullion	1	0	201	5130	1350	0,037	99,9	2	880	100	2340
11b	31.7	alum-mullion	1	0	201	5130	1350	0,034	91,8	2	1000	100	2400
11c	31.7	glass-double	1	2,5	1,1	5350	4600	0,02	184	2	760	12	2220
12a	31.8	woodsandwichpanel	1	0	0,03	2080	250	0,06	30	2	0	0	0
13a	31.8	woodsandwichpanel	1	0	0,03	2080	250	0,08	40	2	280	100	3020
14a	31,9	aluminum	2	0	201	5130	2700	0,00006	9,072	56	100	100	60
15a	31,9	aluminum	2	0	201	5130	2700	0,0002	10,8	20	530	50	65
16a	31,9	aluminum	2	0	201	5130	2700	0,0016	34,56	8	3660	50	65
17a	31,9	insulation	1	0	0,03	2080	32	2,2	70,4	1	0	0	0
18a	32,1	woodsolid	1	0	0,35	2580	890	0,007	791,21	127	150	25	2050
19a	32,1	woodsolid	1	0	0,35	2580	890	0,003	32,04	12	25	100	1200
20a	32,1	woodsolid	1	0	0,35	2580	890	0,004	99,68	28	25	100	1700
21a	32,1	woodsolid	1	0	0,35	2580	890	0,004	56,96	16	0	0	0
Total									**50762,122**				

Product code	Location	Virgin CO2 (kg/kg)	Recycling CO2 (kg/kg)	Recycle efficiency	landfill CO2 (kg/kg)	Transport CO2/m3 per km	Virgin feedstock (%)	Weight of Virgin mass (kg)	Reused feedstock (%)	Weight of Re-used content (kg)	Recycled feddstock (%)	Weight of Recycled content(kg)	Recycled efficiency	Waste of recycled content(kg)	Recycling potential	Weight of recyclable content (kg)
	0	Cv	Cr1	Ef	Cl	Ct	V		Fu		Fr		Ef	Wf	Cr	
0a	hague	0,1	0,1	0,4	0,2	0,026	0	0	1	33600	0	0	0,4	0	0	0
1a	hague	0,23	0,23	0,8	0,46	0,026	0	0	1	2691	0	0	0,8	0	1	2691
2a	hague	3,1	3,1	0,8	6,2	0,026	0	0	1	83,2	0	0	0,8	0	1	83,2
3a	hague	1,83	1,83	0,8	3,66	0,026	0	0	1	705	0	0	0,8	0	1	705
3b	hague	14,6	14,6	0,8	29,2	0,026	0	0	1	810	0	0	0,8	0	1	810
4a	hague	0,1	0,1	0,8	0,2	0,026	0	0	1	10260	0	0	0,8	0	1	10260
5a	amsterdam	1,83	1,83	0,8	3,66	0,026	0,5	105,75	0	0	0,5	105,75	0,8	26,4375	1	211,5
6a	hengelo	2,75	2,75	0,8	5,5	0,026	0,7	196,56	0	0	0,3	84,24	0,8	21,06	0	0
7a	hengelo	2,75	2,75	0,8	5,5	0,026	0,7	196,56	0	0	0,3	84,24	0,8	21,06	0	0
8a	hengelo	2,75	2,75	0,8	5,5	0,026	0,7	65,52	0	0	0,3	28,08	0,8	7,02	0	0
9a	amsterdam	0,7	0,7	0,8	1,4	0,026	1	89	0	0	0	0	0,8	0	0	0
10a	eindhoven	0,7	0,7	0,8	1,4	0,026	0	0	1	106,8	0	0	0,8	0	1	106,8
11a	arnhem	14,6	14,6	0,8	29,2	0,026	0	0	1	99,9	0	0	0,8	0	1	99,9
11b	arnhem	14,6	14,6	0,8	29,2	0,026	0	0	1	91,8	0	0	0,8	0	1	91,8
11c	arnhem	1,83	1,83	0,8	3,66	0,026	0	0	1	184	0	0	0,8	0	1	184
12a	hengelo	0,5	0,5	0,8	1	0,026	1	30	0	0	0	0	0,8	0	1	30
13a	hengelo	0,5	0,5	0,8	1	0,026	1	40	0	0	0	0	0,8	0	1	40
14a	zwolle	14,6	14,6	0,8	29,2	0,026	0	0	1	9,072	0	0	0,8	0	0	0
15a	zwolle	14,6	14,6	0,8	29,2	0,026	0	0	1	10,8	0	0	0,8	0	0	0
16a	zwolle	14,6	14,6	0,8	29,2	0,026	0	0	1	34,56	0	0	0,8	0	0	0
17a	arnhem	3,1	3,1	0,8	6,2	0,026	1	70,4	0	0	0	0	0,8	0	1	70,4
18a	amsterdam	0,7	0,7	0,8	1,4	0,026	1	791,21	0	0	0	0	0,8	0	0	0
19a	amsterdam	0,7	0,7	0,8	1,4	0,026	0	0	1	32,04	0	0	0,8	0	0	0
20a	amsterdam	0,7	0,7	0,8	1,4	0,026	0	0	1	99,68	0	0	0,8	0	0	0
21a	amsterdam	0,7	0,7	0,8	1,4	0,026	0	0	1	56,96	0	0	0,8	0	0	0
Total								**1585**		**48874,812**		**302,31**				**15383,6**

Product code	Recycling efficiency	Waste of recyclable content (kg)	Reusable potential (%)	Weight of re-usable content (kg)	Un-usable waste (%)	Weight of Unrecoverable waste (kg)	Linear Flow Index	Expected Life-time (yr)	Industry Average Life-time (yr)	Utility factor	MCI	MCI * W	Distance from project site	CO2 due to virgin mass (kg)	CO2 due to recycled content (kg)	CO2 due to distance from project site (kg)
	Ec	Wc	Cu		W0	W	LFI	L	Lav				Dp			
0a	0,4	0	1	33600	0	0	0,00	100	100	0,9	1,00	33600,00	0,00	0,00	0,00	0,00
1a	0,8	538,2	0	0	0	269,1	0,05	25	70	2,52	0,87	2334,09	0,00	0,00	0,00	0,00
2a	0,8	16,64	0	0	0	8,32	0,05	0,01	30	2700	0,00	0,00	0,00	0,00	0,00	0,00
3a	0,8	141	0	0	0	70,5	0,05	0,01	50	4500	0,00	0,00	0,00	0,00	0,00	0,00
3b	0,8	162	0	0	0	81	0,05	50	70	1,26	1,00	756,28	0,00	0,00	0,00	0,00
4a	0,8	2052	0	0	0	1026	0,05	0,01	70	6300	0,00	0,00	0,00	0,00	0,00	0,00
5a	0,8	42,3	0	0	0	34,36875	0,34	50	50	0,9	0,75	147,24	50,00	3,87	1,94	5,50
6a	0,8	0	1	280,8	0	10,53	0,36	100	100	0,9	0,67	189,32	150,00	10,81	2,32	21,90
7a	0,8	0	1	280,8	0	10,53	0,36	100	100	0,9	0,67	189,32	150,00	10,81	2,32	21,90
8a	0,8	0	1	93,6	0	3,51	0,36	100	100	0,9	0,67	63,11	150,00	3,60	0,77	7,30
9a	0,8	0	1	89	0	0	0,50	100	100	0,9	0,55	48,95	50,00	1,25	0,00	2,31
10a	0,8	21,36	0	0	0	10,68	0,05	30	100	3	1,00	89,94	100,00	0,00	0,00	5,55
11a	0,8	19,98	0	0	0	9,99	0,05	50	70	1,26	1,00	93,28	75,00	0,00	0,00	3,90
11b	0,8	18,36	0	0	0	9,18	0,05	50	70	1,26	1,00	85,71	75,00	0,00	0,00	3,58
11c	0,8	36,8	0	0	0	18,4	0,05	46	50	0,97826087	1,00	174,53	75,00	0,00	0,00	7,18
12a	0,8	6	0	0	0	3	0,58	30	30	0,9	0,55	14,37	150,00	0,30	0,00	2,34
13a	0,8	8	0	0	0	4	0,58	30	30	0,9	0,55	19,16	150,00	0,40	0,00	3,12
14a	0,8	0	1	9,072	0	0	0,00	66	70	0,95454545	1,00	9,07	65,00	0,00	0,00	0,31
15a	0,8	0	1	10,8	0	0	0,00	66	70	0,95454545	1,00	10,80	65,00	0,00	0,00	0,37
16a	0,8	0	1	34,56	0	0	0,00	66	70	0,95454545	1,00	34,56	65,00	0,00	0,00	1,17
17a	0,8	14,08	0	0	0	7,04	0,58	26	30	1,03846154	0,40	28,07	75,00	4,36	0,00	2,75
18a	0,8	0	1	791,21	0	0	0,50	96	100	0,9375	0,53	420,33	50,00	11,08	0,00	20,57
19a	0,8	0	1	32,04	0	0	0,00	96	100	0,9375	1,00	32,04	50,00	0,00	0,00	0,83
20a	0,8	0	1	99,68	0	0	0,00	96	100	0,9375	1,00	99,68	50,00	0,00	0,00	2,59
21a	0,8	0	1	56,96	0	0	0,00	96	100	0,9375	1,00	56,96	50,00	0,00	0,00	1,48
Total				**35378,522**	**0**	**1576,14875**										

Product code	CO2 of transport to recycling plant (kg)	CO2 due to recyclable content (kg)	CO2 due to unrecoverable waste (kg)	Embodied CO2 (kg/yr)	CO2 of a linear equivalent (kg)	CO2 reduction	Cost of virgin content (Euro)	Cost of reused content (Euro/yr)	Cost due to transport ((Euro/yr)	Cost of transportation of recyclable content (Euro/yr)	Cost of Landfill (Euro/yr)	Cost/yr (Euro)	Cost of linear equivalent (Euro)	Cost reduction	Design stage
						%								%	
0a	174,72	0,00	0,00	0,00	1229,76	100%	0,00	16,80	0,00	0	0	32,31	3259,20	99%	0
1a	13,99	6,19	2,48	43,57	107,48	79%	0,00	37,67	0,00	68,31	14,49	155,25	333,68	76%	0
2a	0,43	2,58	1,03	7,78	13,48	70%	0,00	2,16	0,00	2,11	0,83	7,10	13,56	73%	0
3a	3,67	12,90	5,16	41,78	71,02	69%	0,00	55,34	0,00	17,90	21,29	145,61	178,37	58%	0
3b	4,21	118,26	47,30	0,00	474,66	100%	0,00	14,58	0,00	0,00	0,00	28,04	106,92	86%	0
4a	53,35	10,26	4,10	130,22	892,62	92%	0,00	82,08	0,00	260,45	31,57	449,86	1764,72	87%	0
5a	1,10	3,87	2,52	23,60	21,31	42%	16,60	0,00	69,80	0,00	3,99	170,14	53,51	-65%	1
6a	1,46	0,00	1,16	69,59	52,71	31%	2,36	0,00	277,99	0,00	0,24	539,38	47,17	-495%	1
7a	1,46	0,00	1,16	69,59	52,71	31%	2,36	0,00	277,99	0,00	0,24	539,38	47,17	-495%	1
8a	0,49	0,00	0,39	23,20	17,57	31%	0,79	0,00	92,66	0,00	0,08	179,79	15,72	-495%	1
9a	0,46	0,00	0,00	6,85	5,14	31%	4,04	0,00	29,37	0,00	0,00	64,25	12,58	-165%	1
10a	0,56	0,75	0,30	10,68	6,17	10%	0,00	2,42	70,49	0,00	0,00	140,22	15,10	-383%	2
11a	0,52	14,59	5,83	7,49	58,54	93%	0,00	1,80	49,45	0,00	0,00	98,56	13,19	-289%	2
11b	0,48	13,40	5,36	6,89	53,79	93%	0,00	1,65	45,44	0,00	0,00	90,56	12,12	-289%	2
11c	0,96	3,37	1,35	13,80	13,75	48%	0,00	14,44	91,08	0,00	0,00	202,93	41,03	-157%	2
12a	0,16	0,15	0,06	5,08	3,07	14%	1,56	0,00	29,70	0,00	0,00	60,12	6,24	-401%	2
13a	0,21	0,20	0,08	6,77	4,09	14%	2,08	0,00	39,60	0,00	0,00	80,15	8,32	-401%	2
14a	0,05	0,00	0,00	0,59	5,39	94%	0,00	0,16	3,89	0,00	0,00	7,80	1,28	-217%	3
15a	0,06	0,00	0,00	0,70	6,41	94%	0,00	0,19	4,63	0,00	0,00	9,28	1,52	-217%	3
16a	0,18	0,00	0,00	2,25	20,52	94%	0,00	0,62	14,83	0,00	0,00	29,71	4,87	-217%	3
17a	0,37	2,18	0,87	20,25	11,40	8%	3,66	0,00	34,85	1,79	0,70	76,55	11,48	-247%	3
18a	4,11	0,00	0,00	60,86	45,73	31%	35,92	0,00	261,10	0,00	0,00	571,19	111,88	-165%	3
19a	0,17	0,00	0,00	1,60	1,85	55%	0,00	0,73	10,57	0,00	0,00	21,73	4,53	-149%	3
20a	0,52	0,00	0,00	4,98	5,76	55%	0,00	2,26	32,89	0,00	0,00	67,61	14,09	-149%	3
21a	0,30	0,00	0,00	2,85	3,29	55%	0,00	1,29	18,80	0	0	38,63	8,05	-149%	3

Appendix 4 Madaster Inventory of source files

In order to eventually generate a material passport in the Madaster platform, the platform must first be provided with source files containing detailed data of the specific building (or building section).

The BIM model is central to the Madaster platform, where the universal "IFC format" (.ifc) is seen as the source file for the input of all data of the building. An IFC file is generally created during the

design and / or renovation phase of a building (or building section) in a 3D modelling application such as Autodesk Revit, Archicad, etc. Below you will find the Madaster guidelines for setting up the BIM model and the export of an IFC file:

- Ensure that the project zero point is related to the RD coordinate anywhere in the world (note: Dutch coordination system);
- Prevent the use of the IFC entity 'Building element proxy' and 'Building element part';
- Each GUID must be unique;
- All elements must have a material assigned;
- All elements must be classified by NL/SfB (4 digits): in which a building part or material is located (note: Dutch classification of building elements);
- Enter the "IFC-Type" correctly, enter as much as possible for each element;
- Always export the "Base Quantities" (volume units);
- Export the "Renovation status" or "Phasing" in the eponymous Property set; if self-made, use the English name: Existing / Demolish / New;
- Use the "2x3" export setting.

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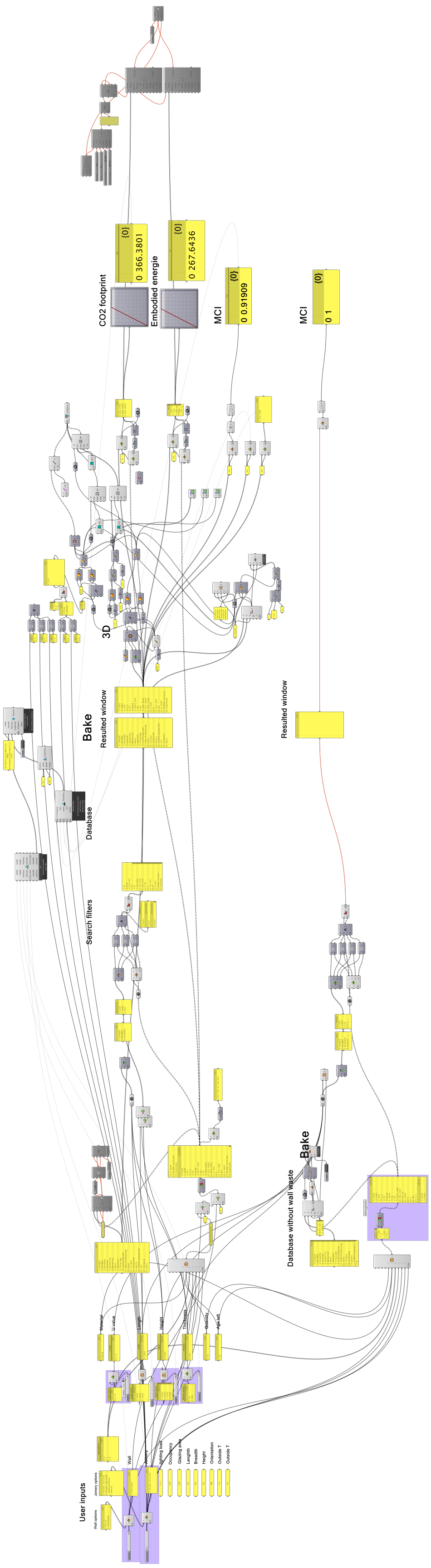
Appendix 5 Visual scripts

Script 1 – For creating an online library of materials - Material Explorer



Script 2 – For creating and online library as well as copying material in the Main database (worksheet) in Excel.